Bricks / Systems

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Introduction

Isak Worre Foged and Lasse Andersson

At first glance, this book may appear eclectic. It contains writings from architectural practice in a language and structure based on subjective views and experiences, combined with research contributions based on systematic design investigations of discrete computational systems. Discussions range from an undulating masonry wall at the University of Virginia erected by then-U.S. President Thomas Jefferson to agile robotic manufacturing processes and computational solver strategies based on graph networks.

Conversely, the focus of this anthology is expressed directly in the title: bricks and systems. The basis for this theme is the work conducted at the Utzon(x) Research Group at Aalborg University, in combination with the rich tradition and implementation of masonry work in Denmark, which has attracted increasing attention from architectural practitioners and researchers alike. From the map (Figure 1) generated by computational processes, the spread and density of brickworks across Denmark become visible. In contrast, the contours of Denmark are visible in their high number and positions across the country. This suggests a critical mass of makers of bricks identifiable as the basis of a strong masonry-based built environment.

Despite the faceted character of this publication, it also reveals to the reader underlying relations between the contributions. The contributions follow a path that begins by discussing the work and conditions of practice, related to research methods, followed by perspectives of experienced and acknowledged practitioners of masonry architecture. This is engaged more deeply via design research related to brickwork, which then links to computational systems that rely on the control and exploration of discrete and interconnected geometric material systems. Furthermore, three

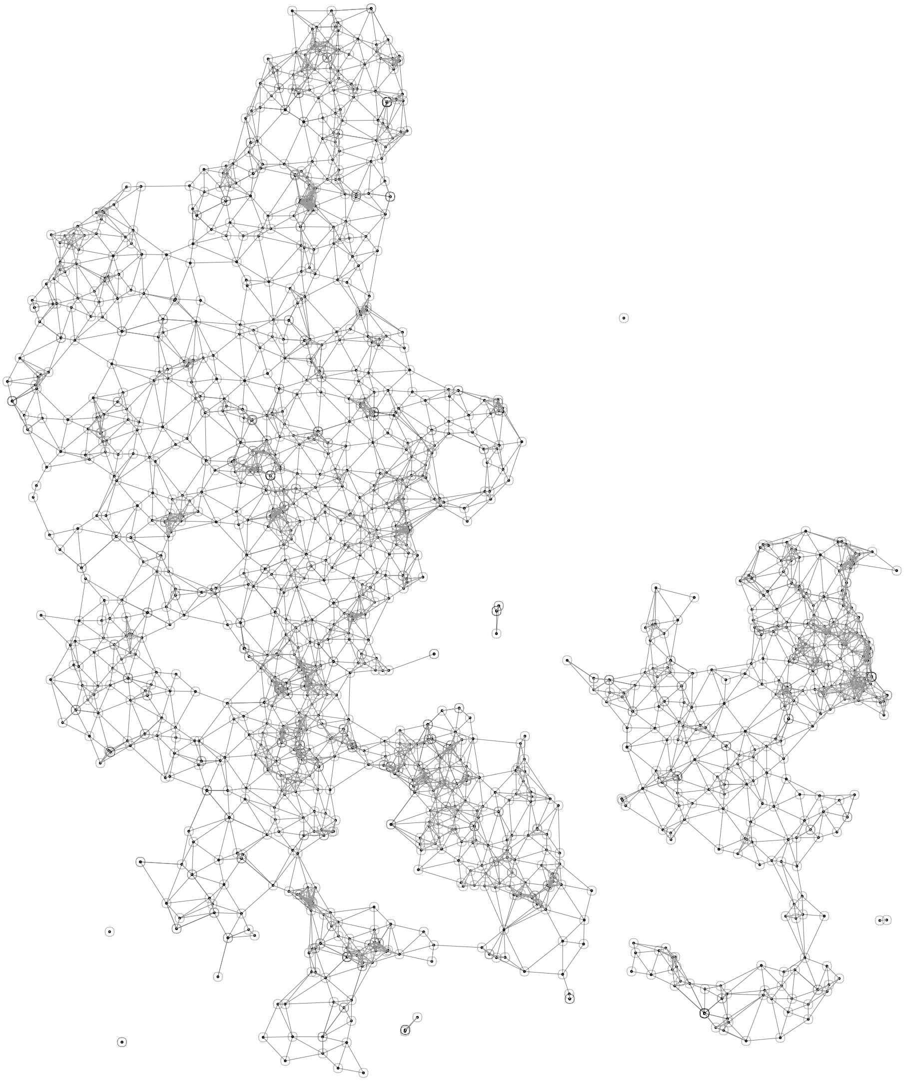

Figure 1:
Map of brickyards in Denmark generated based on Verner Bjerge's semi-structured register.
Map by Isak Worre Foged

contributions are based on the experimental design platform of the Utzon(x) 2014 summer school, exploring different computational approaches to experimental design processes. Obviously, many more interconnections exist. Please construct your own relations and conclusions across this publication as you move through it.

To unfold fractions of the content, a brief tour through the contributions is provided below.

In the second paper, 'Bricks and Sustainability', Lars Juel Thiis elaborates on the inherent qualities of masonry work and its capacity to increase its sustainability as time passes. This forms a constructive critique of how we assess sustainability in contemporary architecture and how bricks can become an instrumental part of addressing the multitude of questions currently confronting the built environment.

In the third paper, 'Rethinking Brick', Kjeld Ghozati illustrates how small modifications to the geometry of the standard Danish brick may allow new ways to assemble and compose masonry structures and how this in turn supports new variations of masonry constructions. Textures, colours, decoration, assembly logic and structural properties are all at play.

The generic qualities of bricks are most elegantly utilized in new fabrication techniques and architectures in 'Robotic Brickwork: Towards a New Paradigm of the Automatic' by Tobias Bonwetsch, Jan Willmann, Fabio Gramazio and Matthias Kohler. The premise of the paper is the remark that the simplicity of the element allows the complexity of the assembly. This pioneering work on the articulation of masonry structures by robot manufacturing processes presents both new possibilities and questions regarding contemporary brickwork in architecture. While offering a new agenda for masonry works, the paper may also provoke conversations about how we will construct the built environment in the future.

In 'Synthesizing a Nonlinear Modelling Pipeline for the Design of Masonry Arch Networks', Anders Holden Deleuran exemplifies how computational systems can advance our methods and thinking with regard to the organisation of masonry arch structures. Furthermore, the usefulness of the presented, developed and applied computational systems appear to embrace complexities inherent in many other architectural problems that deal with complex hierarchical structures of information.

In similarity, 'Digital Simulation for Design Computation in Architecture', authored by David Stasiuk and Mette Ramsgaard Thompsen, elaborates on the nature and deep potential of design computation and simulation processes. As strategies and techniques, computational systems are discussed in relation to developed research through design case studies, illustrating the capacity to work with multi-authored design systems.

Related to the above two contributions is the paper 'Finding Thermal Forms: A Method and Model for Thermally Defined Masonry Structures', authored by Isak Worre Foged. Here, computational processes involved in thermal simulations, combined with search algorithms, form a methodological core illustrating how masonry structures can be articulated by their thermal capacities. The work adds to the previous studies and contributions by focusing on structural and optical aspects of masonry, such as formal language and ornamental expressions.

While the previous four papers focus on the combination of masonry structures and computational systems, the contribution by Daniel Bosia, 'Design of Structural Skins', points to modularity and 'brick' assemblies composed of other materials and geometries

than clay bricks. The control and organisation of discrete elements for manufacturing and design evolution is presented and discussed through a series of built projects by the author and partners.

Similarly, Sigrid Adriaenssens describes 'Dialectic Form' principles based on material and computational systems, which negotiate the contrasting demands and intentions towards new possibilities in architecture. The explicitness of material properties as a central constituent in any computational design system is vividly articulated through explorations of structures built using chocolate.

And, the first paper of the anthology discusses and elaborates on the methods and models in practice and research towards novel architectural conjectures of making and thinking. In this paper, 'Experimental Vectors of Practice and Research in Architecture', Isak Worre Foged proposes working with hybrid experimental models based on literary studies in architectural theory and philosophy of science and illustrates case studies of two Pritzker Laureates who pioneered architectural practice.

From these contributions, the title 'Bricks / Systems' has emerged.

How should one understand this book, with its widely varied yet converging contributions? As stated by German architect Frei Otto (Songel 2010), buildings should be understood as auxiliary means—they are not ends in themselves. We believe this book should be understood through the same lens. It connects, rather than concludes, and it aims to illustrate and identify new modes of working in architecture, particularly with regards to brickwork and other complex systems of modular assemblies, whether physical or digital. The faceting and complexity arrives from the interdisciplinary working methods, which we believe to be the basis of future architectures.

This publication is based on contributions from the Utzon(x) 2014 summer school, symposium and associated exhibition 'We Love Bricks' at the Utzon Center and Aalborg University, Aalborg, Denmark. We are grateful for the support of this work by the Department of Architecture, Design and Media Technology and the Utzon Center. It is privilege to receive substantial financial support for these activities. We are tremendously thankful for the backing by the Obel Family Foundation, which supports the development, operation and dissemination of the Utzon(x) summer schools, and to the Realdania Foundation for supporting the exhibition and book publication. The credit for the work produced here rests with many people; hence, we would like to thank the students, administrative staff, practitioners and academics who have contributed to the making of ideas, methods and models captured in this book.

Songel, J.M., 2010. A Conversation with Frei Otto, Princeton Architectural Press.

Experimental Vectors of Practice and Research in Architecture

Isak Worre Foged

This paper targets practising architects with an interest in architectural theories and methodologies, academic architects and experimental researchers in architecture. It aims for the advancement of architectural thinking towards instrumental models that improve both creative solutions and problem-solving aspects.

It attempts to identify and discuss the possible connections and shared terrain between practice and research in architecture. It also proposes the development of more hybrid explorative models that support both the diversity and the specificity of architectural proposals, ultimately towards supporting a general higher quality of the built environment.

To visualise theoretical notions and practice-oriented processes, vectors are initially used as metaphors, which in turn form the basis for the provided diagrams of architectural processes. Following the clarification of these processes, experimentation as the common catalyst and denominator is further discussed, including two case studies. Lastly, the conclusion and the discussion of the arguments are presented for further questions, analyses and studies in the fields of architectural theories and methods and models for instrumental, experimental architectural design.

Based on the above objectives, it can be asked: Are practice and research converging in architecture?

This question is open-ended, non-contextualised and unspecified, hence difficult to address without further clarification of the inquiry. If we consider whether the modes of thinking and doing of practice and research are becoming more related, we approximate an examination of the two fields of architecture, which might help support

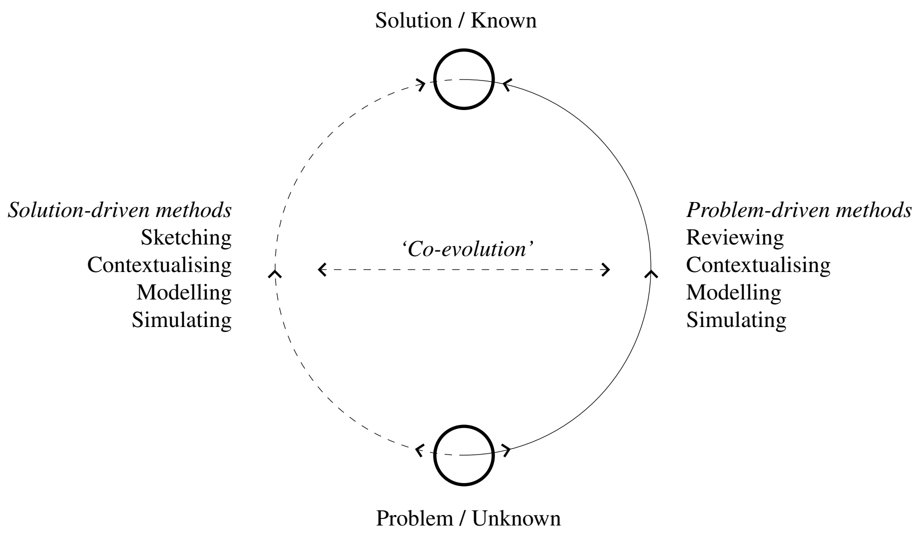

Figure 1:
Strategies and methods related to practice (left course) and research (right course) in architecture, interwoven as co-evolution where strategies are combined. Diagram by author.

the development of both, whether entangled or not. Rather than asking why there may be differences between practice and academic research and whether these differences are instrumental to or demarcating architecture as a whole, the objective here is an attempt to identify and discuss possible instrumental correlations, which may cross-inform and support the development of the two domains.

When considering the two domains as vectors, they are represented by a starting point and a direction. What are the starting points in practice and research?

Starting Points

In practice, an architect is typically confronted with a request to design a building. The aim is a design, which can be formulated as a response to a problem (Lawson, 2006). The axiom of the design process is not necessarily formulated as a problem, but it can be articulated as a problem in relation to fulfilling a specific spatial programme, in a particular context, with restrictions in economy and so on. While often applicable, the description of an architectural process as stimulated through a specific problem cannot be taken for granted (Dorst and Cross, 2001; Dorst, 2006; Dorst, 2007). Just as often, the starting point is a condition or a potential, which sparks an interest to create a solution despite the absence of an identified problem.

In academia, a researcher often addresses a specifically described problem or unknown condition, based on an "indeterminate situation" (Mackay, 1942; Strübing, 2007) where something cannot de explained. The aim is knowledge. For this reason, the starting point is knowledge and missing knowledge. In the given context, the missing knowledge is described via a problem formulation. In design research (as in e.g., economy), what is studied is something produced by humans, denoted as an "artificial construction" (Simon, 1996), in opposition to the already present physical constructions that can be observed in physics, chemistry and biology, for example. This means that human construction needs to take place before observations and further constructions can be developed based on these observations.

Directions

Some studies indicate that designers are solution focused (Kruger and Cross, 2006; Lawson, 2006), directing their efforts towards proposing possible solutions as the primary process method (Figure 1). This initiates an unstructured trial-and-error process, which generates multiple variations of one or more solutions to an ill-defined condition. It is based on incomplete models (Lawson, 2006) and methods that allow variations to be created rapidly (Akin and Lin, 1995). In contrast, science and engineering processes are based on problem-focused systemic processes, each with a clearly defined goal and method of investigation (Archer, 1995), attempting to identify the basis of each condition to propose a solution through a more complete model, which often requires an extensive setup and expert background knowledge. Furthermore, design research methods can be dissected into the three categories of *theoretical-conceptual* research *into* design, *methodological-instrumental* research *for* design and *experimental-hypothetical* research *through* design (Frayling, 1993). This paper can be categorised under the first two types, while the third path is what is studied and discussed. The latter points to processes of making, as is the core of practice, which from an anthropological position is argued to support an improved possibility for understanding a given problem or condition in a specific context based on the direct relation to the object studied (Ingold, 2013). Observations of these processes in the literature therefore suggest that the two fields operate with different directions, governed by a stochastic and open process in

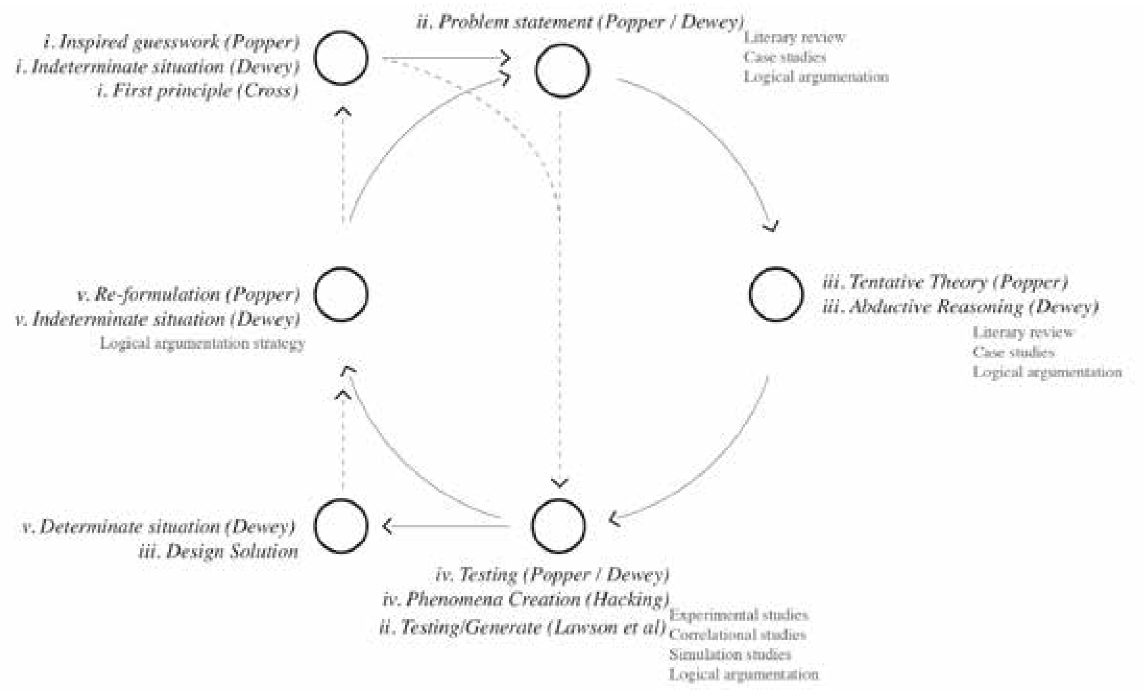

Figure 2:
Processes of making and thinking in science and architectural research (solid line) and practice (dotted line), with the denominator of testing/experimentation. Diagram by author.

practice and a deterministic and narrow process in research.

With the above arguments, it seems straightforward to maintain a clear separation in the directions of the fields. Nevertheless, computer science studies of algorithmic structures that search for an answer or a solution to a starting condition point to a potent application of both approaches as a hybrid method of progress. The computer science studies conclude (Maher and Poon, 1995, 1996) that the ability to stochastically search, evaluate and evolve potential solutions could be described as co-evolution processes, which integrate methods of solution making and problem identification in parallel. This dual process has subsequently been observed in the creative processes of expert designers (Dorst and Cross, 2001) and how these different strategies effect the outcome of design in terms of quality and creativity (Kruger and Cross, 2006). While a solution-based strategy supports generative processes, a problem-based strategy increases the ability to identify problems. Interestingly, the number of designers for each strategy is almost the same, contradicting the prevalent idea of designers being primarily oriented towards solution-based thinking and associated methods. With qualities assigned to both approaches, co-evolution by hybrid strategies (methods and models) appears to be an instrumental platform for both practice and research endeavours.

When diagramming the solution- and problem-based process (Figure 2), based on descriptions of the mathematician and philosopher of science, Karl Popper (1959, 1985), the philosopher of science, John Dewey (Strübing, 2007) and the design process researcher Nigel Cross (2002), among others, there are overlapping strategies and sub-processes in practice and research. The initiation of research processes is based on *inspired guesswork* and *indeterminate situations*, while expert design processes apply *first principles*. While researchers enter the process of reviewing the literature to detect prior knowledge and studies of relevance, practising designers attempt to identify a problem by proposing a solution through testing/making processes. Based on the problem framing in academia, researchers formulate initial theories, which frame the basis for testing. The common sub-process in both practice and research is measuring/making to test an axiom condition. Through the specified problem framing and delineation by tentative theory making in research, testing is specified for models, with isolated and controlled variables. One such test strategy could be parameter or sensitivity analysis, while in practice, it becomes the ability to generate variations (Speaks, 2002), which supports a better understanding of what aspects are relevant and what their variable boundaries are.

Processes of experimentation by testing through making, simulating and measuring are essential to both practice and research activities. This suggests a further identification of what an experiment is and can be in architecture. What can be expected from an experiment, and how can an experiment be framed and explored in architectural research and practice?

Gothic cathedrals were erected in ever more daring designs; some collapsed, and new ones were constructed. For centuries, such processes of building constituted the only way forward, by trying, failing and trying again. The essence of these processes is a goal-oriented, trial-and-error methodology by modifying structural parts or rebuilding whole organisations in an iterative process. Thus, as discussed above, experimentation is part of the architectural discipline that searches novelty and hence has been at the core of an evolving practice. Nevertheless, today, we generally consider experimentation in

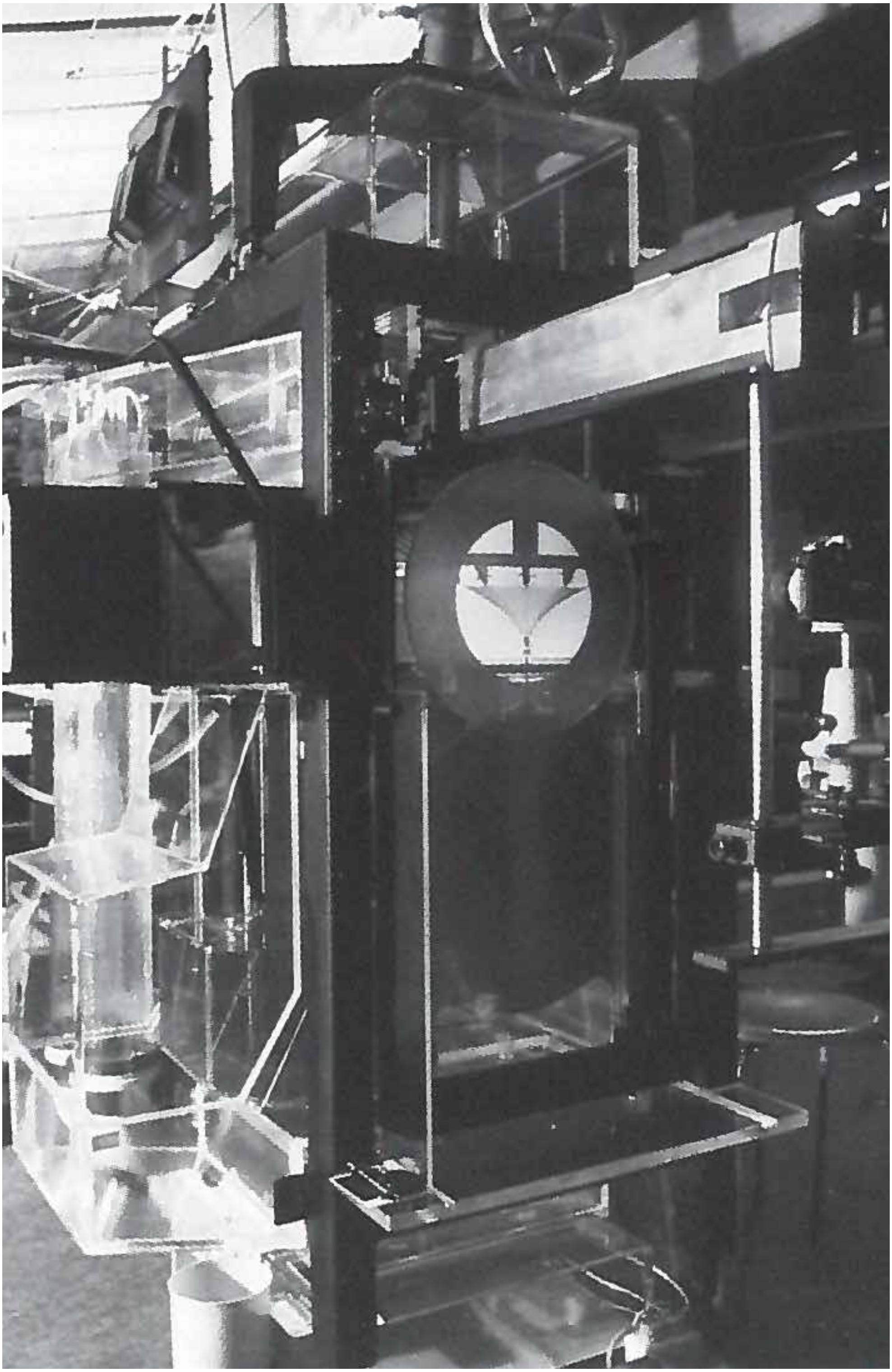

Figure 3:
Frei Otto's soap film machine at the Institute of Lightweight Structures in Stuttgart.
Photo from the book Finding Form (Otto and Rasch, 1996).

architecture as a novel activity, as observed in specialised groups, such as the Advanced Geometry Unit (AGU) and Foresight, Innovation, Incubation (FII) at Arup and GXN at 3XN and Smart Modelling Group (SMG) at Foster and Partners. Despite its immediate necessity in architecture, experimentation is a method that is seldom applied to a design solution in common practice (Speaks, 2007). This general shift to abandoning experimentation was based on the separation of the renaissance architect from the physical building process, by using drawings to represent buildings (Hill, 2011). The representational drawing as the architectural medium caused a clear separation between the thoughts on the visual style of the architect and the physical construction of the craftspeople, in contradiction to learning and developing while building, as was practised prior to the renaissance architect. Now, as a new understanding of the experiment in architectural practice and architectural research is emerging, we may reconsider what an architectural experiment is and how we make it instrumental for our undertakings in both practice and research.

The Oxford Dictionary (2014) defines an experiment as "a scientific procedure undertaken to make a discovery, test a hypothesis, or demonstrate a known fact". Hence, an experiment as an activity is situated in the philosophy of science or how we conduct investigations according to scientific practice. Although this paper is directed by an architectural experimentalist trajectory, we shall briefly review the classical science approach related to experimentation.

A natural science approach, pointing back to Francis Bacon's methodology of observing from "afar" as practised by scientists, established a strong belief in the pure objectivity of human inquiry into how and why the world was constructed as it was. An experiment was aimed to establish how existing conditions in our world came to be.

As argued above, in architecture, we can suggest that humans construct worlds (Chu, 2006); thus, this concept becomes part of how we understand and develop such architectural constructs. The current predominant scientific research methodology of verification and falsification, proposed by Popper (1959), aims to flip the method of argument so that the experimentalist attempts to falsify a condition rather than verify it. The reason for this method is that by verifying something, we cannot know if the verifying conclusion can be generalised and applied elsewhere, outside the specific experiment. By falsification, generalisation is inherently secured. From the scientific research cycle (Figure 2), Popper suggests that through constant systematic investigation, the researcher moves closer to a truth; thus, any truth on the way forward is a normative truth based on the conditions of the experimental setup.

What Popper proposes is a stringent, exact and seamless procedure of the scientific rigour of falsification. However, according to other notable philosophers of science, Thomas Kuhn (1962), Ian Hacking (1991) and Imre Lakatos (1978), the truth is that the process of scientific work is commonly less stringent and often disorganised, chaotic, in varied tempi and often non-linear with truth hierarchies. Nonetheless, in this goal-oriented (Frayling, 1993; Archer, 1995), systematised messiness of formulating a theory, a model and an experiment, ideas evolve and are challenged towards verification. As Hacking (1991) asserts, phenomena are created, which are often found in the abnormalities inside the experiments, usually considered experimental setup imprecisions or indeterminate experimental noise. Hacking proposes that researchers target the experimental efforts towards this noise, these unpredicted phenomena that are occurring when experimenting. In fact, Hacking further suggests that scientific

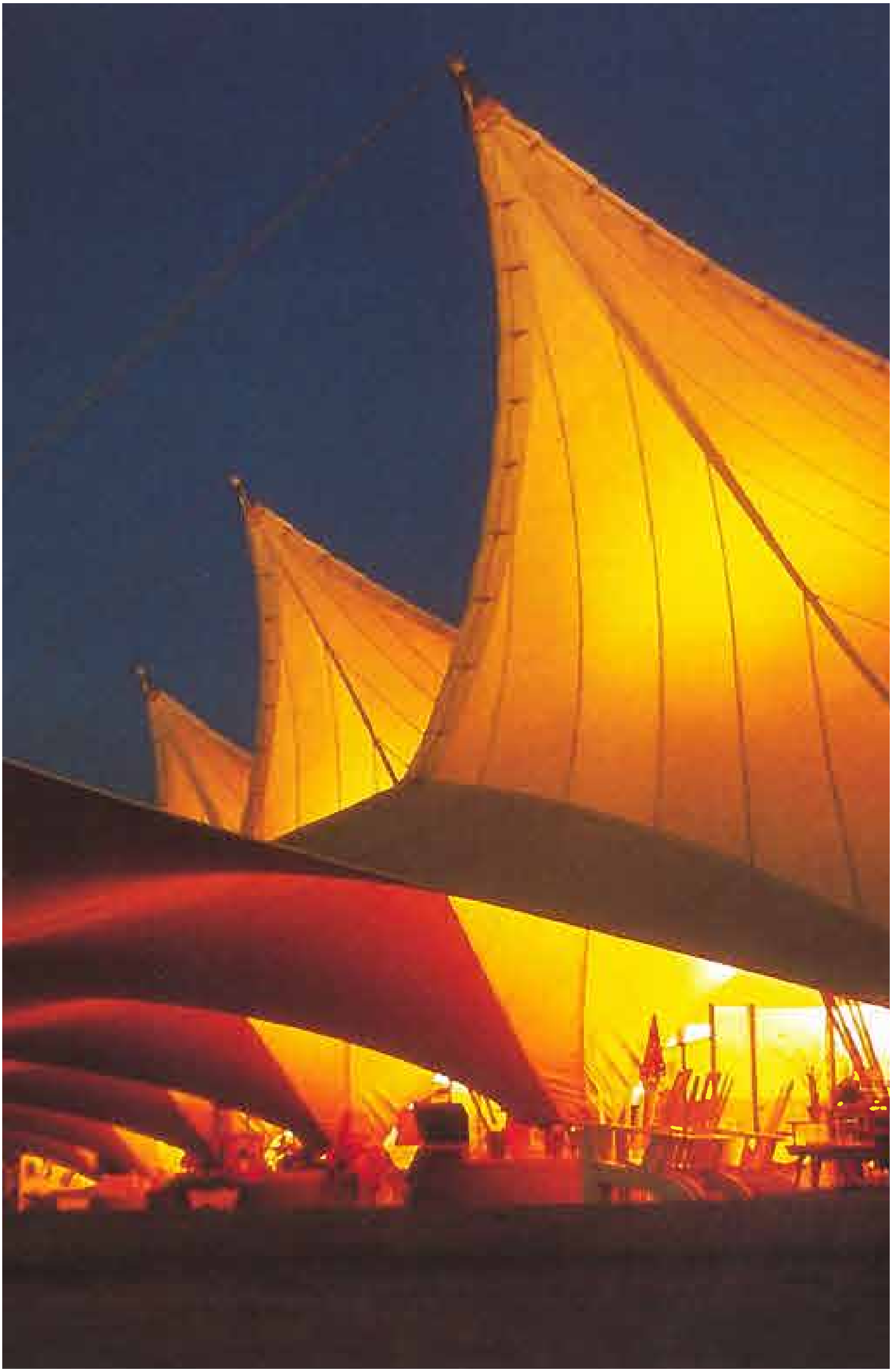

Figure 4:
Minimum surface architecture used in the Great Wave Hall project at the International Garden Exhibition in Hamburg, 1963. Photo from the book Finding Form (Otto and Rasch, 1996).

experiments should not only verify or falsify but equally construct phenomena that can be pursued in new studies.

Experimental studies in architecture then become an architect's instruments for phenomena creation. In turn, this allows observations, where the agency of the experimentalist intervenes through the setup, modification and reading of the studied behaviours, forming the basis for new inquiries and practical experimental investigations. As architectural practice's main activity is to produce constructs and phenomena for humans, a potential wealth of investigatory material and understanding is implicitly present. The creative-based, solution-oriented approach in architecture therefore supports potential scientific advancements, in turn supporting the claim of applying co-evolution processes.

A philosophy of architectural processes based on experiments may thus pursue the notions of Hacking (1991) and others to move architectural practice and research into a position in which these domains will be able to construct verifiable conclusions while increasing novel contributions through a method of phenomena creation by experimentation. The physicist and philosopher of science Allan Franklin (1981, 2016) further elaborates on this argument, discussing the wide range of roles and instrumentalities provided by an experiment. He points to the diversity in which we can understand and apply experimentation in the pursuit of knowledge, problems and solutions (1981, 2016). The descriptions support Hacking's (1991) arguments, adding to the experiment being a place for reflection (Schön, 1984), creating a place for evidence of a thesis (Franklin, 2016), as a method of speculation (Binder and Redström, 2006) and as an interface (Star and Griesemer, 1989). Clearly, experimentation is a method of inquiry that is more open and exploratory in nature than what some natural sciences promote.

Thus, the architectural experiment as a catalyst for architectural inquiry is well aligned with current ideas of scientific progression, but it asks the designer to follow both an open exploratory (creative solution-based) approach and the research (rigorous problem-based) conduct of natural science. From this, we can consider the following questions: How do we experiment? What media of experimentation are relevant to architecture?

The above questions are addressed through the reading and observation of the works of two Pritzker Laureates – Frei Otto and Jørn Utzon. Both architects are highly productive in terms of making and thinking about their creative and observational processes. Additionally, they are both specifically interested in the observation of natural systems and their relations to internal structures and the human environment, connecting them to the dual interest represented in the natural sciences and the humanities. The German architect, engineer and 2015 Pritzker Laureate Frei Otto states:

> *I have developed an entire series of inventions that have their origin in this combinatorial analysis. But the truly important things did not arise from that method, but largely from fortuitous or casual observations made during experiments, some of which were planned in a completely systematic style. ... I am convinced that one can't invent anything by working only systematically* (Songel, 2010, p. 32).

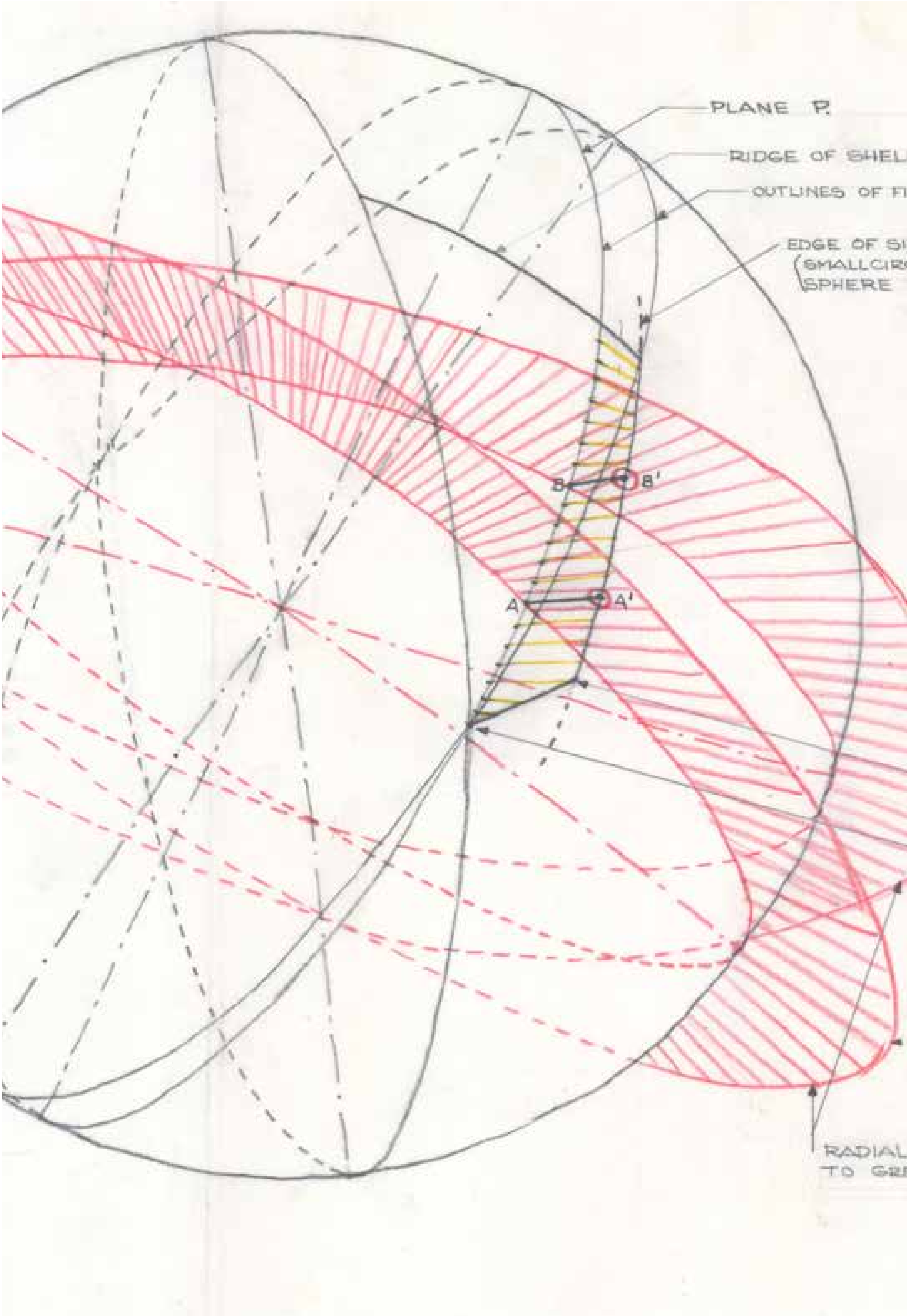

Figure 5:
Drawing of modular assembly patterns on different scales, derived from geometric-based sketches.
Drawing by Jørn Utzon from the Utzon Archives at Aalborg University.

Otto is very conscious about his mode of working and how he can catalyse open ideas in both directed and more stochastic processes of making. In this process, Otto has constructed a physical apparatus (Figure 3), from which conceptual and concrete experiments can be extracted, helping develop the final verification of ideas (Otto and Rasch, 1996; Songel, 2010). Otto notes that there is no way around physical testing and experimentation to avoid failure in relation to what will and will not work but equally important, as means to create novel ideas. The working methods applied are strikingly close to the philosophy of science descriptions of Hacking (1991) and Franklin (1981, 2016) when suggesting what can and should be extracted from experimental procedures. The physical models created by Otto are phenomena machines that allow not only verification/falsification processes, as he intended, but also the construction of yet to be seen and explored built conditions.

A comment from the Pritzker Prize jury (Palumbo, 2015) stresses that Otto's work is multifaceted and offers much more than the buildings he has created. His contributions range from material and structural static knowledge in built works (such as the Munich Stadium and the Mannheim Multihalle) to developed methods of scale experimentation, which have become ways of generating new ideas in his own practice. Educators have subsequently adopted these as methods of learning across progressive architectural institutions (Hensel and Menges, 2006).

In 2003 Pritzker Laureate Utzon's work, we witness an experimental approach that uses other methods than Otto's, specifically in his additive plan systems (Prip-Buus, 2009) and geometric and material studies across architectural scales (Weston, 2008; Andersen, 2011; Foged, 2012).

Utzon's studies of modular and additive assemblies, from the bead and cove brick system to family dwellings and large institutional buildings, exhibit a systematic approach. In his analysis of the underside of a sparrow hawk's wings, he notes:

> *The wings of a sparrow hawk are covered with 2 systems of feathers, respectively 6 rows and specifically formed secondaries and primaries with powerful barbs – and 13-14 rows of secondaries closest to the body...*
> (Utzon, 2009, p. 5).

From the analysis, he concludes:

> *The entire bird is an elegant directional form and construction in which, in clearly directional and additive systems, the feather tracts are subordinated to the main form and function* (Utzon, 2009, p. 5).

This method of analysis and later conversion to modular systems support the exploration of possible configurations that result in an architectural proposal, as well as the search for tools and systems that allow the unfolding of new methods yet again, leading to the detection of problems and potentials in modular assemblies, among others. Additionally, modularity through additive design processes gives Utzon the twofold possibility of a design system with integrated industrial fabrication properties. The design model includes the knowledge of material, geometric and fabrication constraints, while maintaining freedom of configuration between the modular elements and the complete building. Regarding the making of the Sydney Opera House shells, Utzon notes:

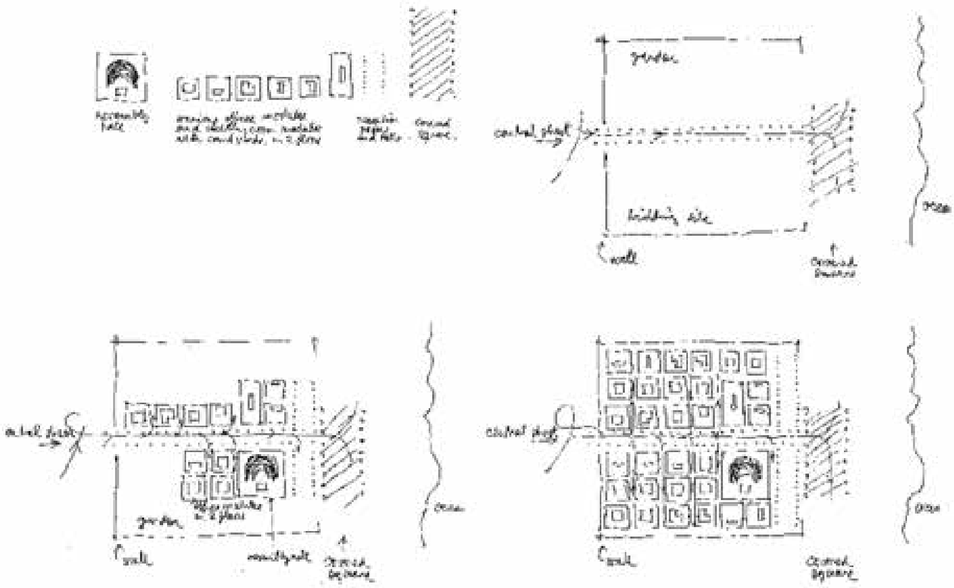

Figure 6:
Jørn Utzon's sketches of modular assembly logics addressing local (element), regional (system) and global (formation) conditions of the Kuwait National Assembly's large complex.
Sketch by Jørn Utzon from the Utzon Archives at Aalborg University.

We can see the use of the same tools for the forming of the curves but extended or reduced as required to obtain the physical size of the panel. By using this same form[,] we have harmony and uniformity throughout[,] giving the intrinsic whole to the building (Government of Australia, 2002).

Similar to Otto's, Utzon's working methods and models operate across multiple scales. He states:

When you work on the basis of the additive principle, you can without difficulty respect and honour all demands concerning the shape of the ground plan and rooms and all demands for expansion and alterations... (Utzon, 2009 [1970], p. 28).

Despite the models' explicit properties, they become multi-objective instruments for exploration, verification, documentation and communication of ideas. Sketches operate across scales, utilised for system thinking (e.g., modular, geometry and assembly logics), abstract phenomena representation (e.g., cloud and plateaus, and branching structures) and exact phenomena representation (mathematics). Scale models are used for system thinking (e.g., additive architecture projects), physical testing (e.g., soap film, modular assemblies and chain models) and representation of ideas. Full-scale models are used for physical testing (e.g., the tile modular system of Sydney Opera House) and as verification materials.

The experimental approach and work across scales can be clearly identified in Utzon's studies during the development of the Kuwait National Assembly structure, where the wall openings and the proportions of each module are related to the entire composition of the large complex (Figure 6). This has created a method containing an "element, system, formation" structure (Foged 2012), which Utzon has used in numerous projects. Otto has also applied the method to his work with tensile membranes, as shown in the relation between the seam of the textile sheets and the overall geometry of the building (Figure 4).

The making of methods and models with generative properties, whether material-based form finding in Otto's studies or additive modular assemblies in Utzon's studies, appears to be central in architectural experimentation processes, which support a co-evolution process towards novel conjectures. Such experimental trajectories in architecture are further discussed in the integration of computation as moving with and beyond the works of the above-mentioned architects.

Two experimental approaches from other design fields that are closer to natural science and engineering have recently been adopted by architecture as a way to create buildings, specifically, simulation and algorithms by digital computation. Strictly speaking, simulation is based on algorithms, but here, they are separated into two categories, with simulation signifying the description/representation of an environment, while algorithm represents the making of architectural forms. First, let us examine simulation as a method of architectural experimentation.

The presupposition for simulation research is that knowledge of a reality can be obtained by reproducing that reality in some substitute medium. David Wang elaborates:

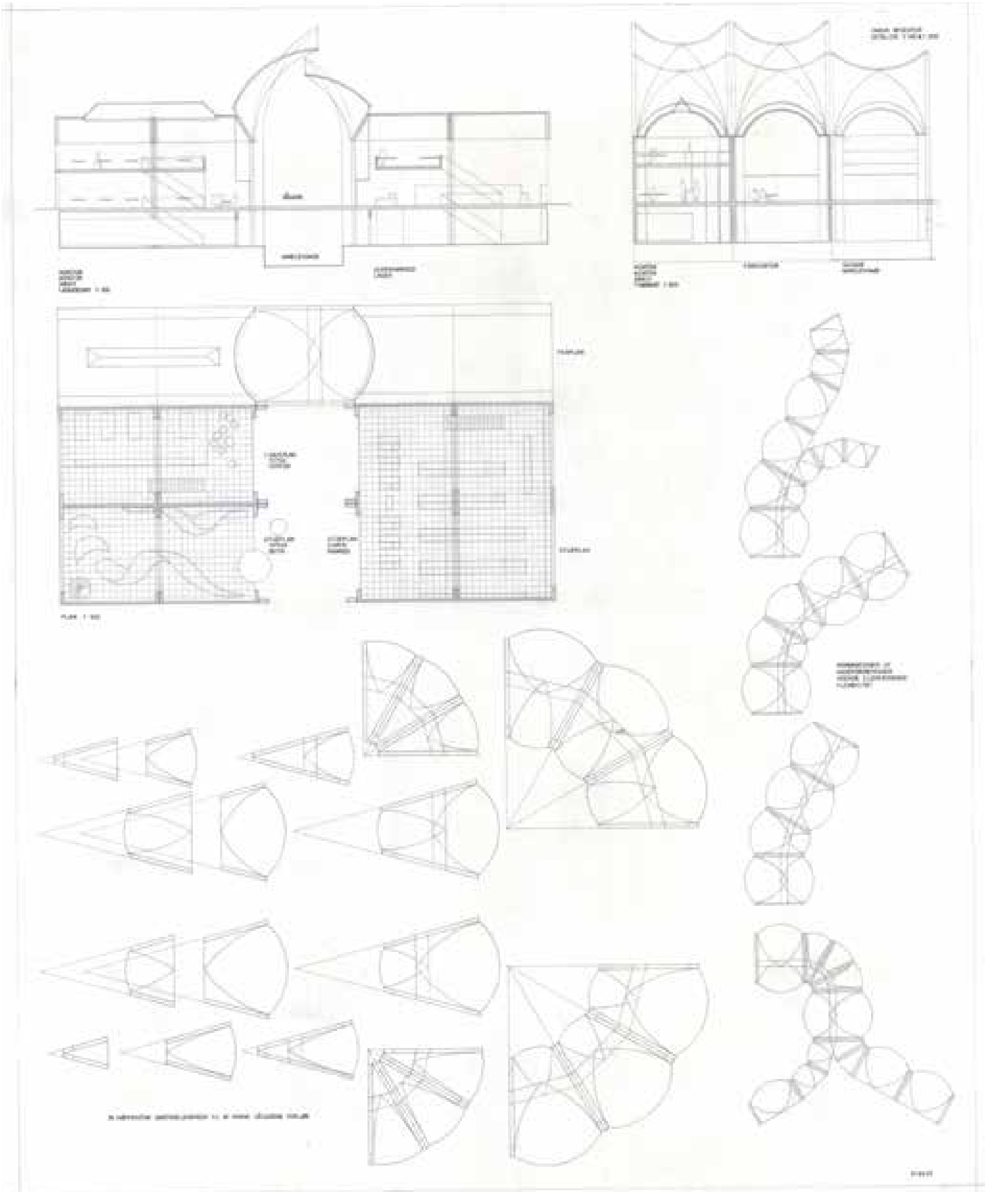

Figure 7:
Jørn Utzon's sketches of modular systems in the Farum Center project. Nested modular systems, with variations in size, geometry, assembly logic, spatial expression and formation capacities.
Sketch by Jørn Utzon from the Utzon Archives at Aalborg University.

> *In a general sense, simulation research is useful both in developing theory and in testing theory… This is particularly true for theory-driven proposals for how physical environments can enhance (or otherwise alter or benefit) some aspects of life* (2013, p. 278).

More specifically, simulation can be performed in both physical and abstract mathematical settings, where simulations rely on abstract numerical expressions to capture real-world relationships (Clipson, 1993). While most simulation procedures, such as reverberation time for acoustics and mean radiant temperature for thermal sensation modelling, are based on mathematical descriptions, other parts of the utilised and developed methods and models cannot be said to be limited to mathematical and numerical expressions. As stated, several simulation models are based on algorithms, which can be described analytically through mathematics but are based on logical procedures with solving properties.

Claims about the imprecision of simulation as an experimental research method have been made, based on the lack of interference with the real world as compared to physical experiments. Throughout his work, Frei Otto has been strongly sceptical of the nature and verifying basis of computational models. As late as 2010, he stated:

> *The computer can only calculate what is already conceptually inside it; you can only find what you look for in computers. Nevertheless, you can find what you haven't searched for with free experimentation* (Songel, 2010, p. 38).

Still under discussion, arguments for the use of simulations are becoming increasingly stronger. One such argument explains that the reductionist procedures often constitute a necessary part of constructing a physical experiment, whereas a simulation can be more inclusive (Hartmann, 2005; Winsberg, 2010). While this is certainly the case for the investigation of "intergalactic gas exchange processes", in architecture, it is arguably a rather different situation as the objective of the inquiry is quite literally more tangible and constructible as a physical experiment. Nevertheless, considering the complications of physically making the weather conditions or an urban field or a complex building and systematically modifying these conditions to understand behavioural effects, a digital computation model exhibits significant capacities for the experimentalist to explore the conditions in a shorter time and with greater control of the included variables. Often, a physical experiment would simply not be possible at an architectural scale. Second, the simulation allows prescriptive research by enabling complex, non-linear and time-based integration processes, where the mere complexity and time span considered would be, if not impossible, infeasible in physical models.

In his book Science in the Age of Computer Simulation, the philosopher of science Eric Winsberg (2010) encourages such an approach by elaborating on the notions and implications of simulation methods for experimental work. He gives numerous examples supporting this claim, illustrating simulation as a method for hypothesis generation, theory building, verification and validation, underlining an epistemology of simulation as a whole. Beyond these aspects, he demonstrates the need for the representational methods used by the simulator. As data are produced during simulation, they can only be observed and understood through a conversion to the visual identification of the human who interprets and potentially interacts with the simulation outcome. While this aspect may seem secondary, the success of simulation as an experimental strategy for the observation of phenomena relies heavily on the output and communication of data (Winsberg, 2010, p. 18). While Otto's models typically explore structural phenomena, it is significantly more difficult to make, control and analyse physical models that investigate environmental effects. One reason for this is that structural load paths are transferred in solids, while environmental phenomena are transferred in solids, gases and fluids.

Experiments that use algorithms to generate formal organisations (the architectural designer's primary activity) necessitate another creative and cognitive design process (Terzidis, 2006). The reason is that when designing with algorithms, a logical procedure is first developed, which then unfolds as a form over time and in space. Various design approaches have been implemented, from direct generation of geometric forms through "shape grammar" and "cellular automata" methods to indirect modification and evolution of forms through "evolutionary" algorithms. While Utzon has not worked with computational generative systems, his additive and modular assemblies are inspired and based on the same underlying principles and structures from which the algorithms are developed. His approach of considering elements, system logics and formations aligns closely with the ideas embedded into computational generative design systems, where the design novelty lies in the development of the logical structure, its building blocks and the resulting formations into a whole. The solution-based outputs are modular combinatorial solutions and constructs of many variations from a relatively simple starting point. These methods share the diversity of formal outcomes and the relations across architectural scales. However, important differences exist because in the computational-making process using a generative procedure, the designer must observe the formal development rather than explicitly draw it. This marks a significant distinction from Utzon's models, where he has continuously interacted with his design system and has developed its structure during this co-evolution process.

Hence, if a computational algorithmic model discards these interactive properties, as observed in both Otto's and Utzon's works, it will challenge the capacities of rapid interaction between the solution and the problem fields. The novel variations will then decrease, caused by "bounded ideation", which is a limitation in creative solution processes by the singularity of working with a digital model, and by "circumscribed thinking", which refers to creative and cognitive processes decreased by the limitations of the digital model (Robertson and Radcliffe, 2009). However, if such mechanisms could be incorporated into the computational generative procedures, new hybrid experimental models would allow exploratory and emergent organisations in which new conditions and phenomena would be created.

In an attempt to answer the posed questions in reverse order (starting with What are the media relevant to architectural experimentation?), it can be suggested that the media of architectural experiments can be abstract sketches for systems thinking, physical models for testing, and computational simulation and generative systems. This is not new, however; what is important is the understanding that the integration of the solution-based and problem-based cognitive processes must be present within these media for experimentation towards novelty in architecture. This requires methods and models, which are open to fast and intuitive modifications of both solution and problem descriptions. This point has been argued in the case studies of Otto and Utzon, literature studies on cognitive design processes and the emergent understanding in the philosophy of science towards the notions of phenomena creation. Any study requires a specific method and model with these properties, which therefore must be evaluated against their co-evolution properties. What can architectural experiments provide? From such models, the experiments in architecture can be expected to produce verification, validation and novel conditions through the creation and identification of new phenomena. In this respect, architectural experiments align closely with the objectives and the results of the natural sciences. While practice and research in architecture may have different starting points, they should both be directed by co-evolution processes, which are argued as fundamental for novel experimental studies. When applying such experimental processes in practice and observing the research cycle diagram (Figure 2), practice and research appear to converge in architecture.

The entanglement between academia and practice in architecture seems to increase the quotient of novelty making, which thus becomes an argument to enhance the interaction and collaboration between academia and practice. While rigour and systematic studies are necessities in research, intuitive and fortuitous processes are increasingly acknowledged as forming a basis for invention and truth finding in the natural sciences. What remains open is how to develop, structure and balance the two processes of solution and problem finding, as identified in Otto's and Utzon's works. We may then ask the following questions: How do we improve our abilities to analyse and observe phenomena in unstructured models of making? What knowledge and skills are required to build methods and models that support new co-evolution design processes in architecture?

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Bricks and Sustainability

Lars Juel Thiis

The brick is a universal material - in spite of our tendency in Denmark to designate the material as specifically Danish. But it does feel Danish, maybe due to the course of history where every Danish parish had its own brickworks. The brick became a part of the collective identity and cultural heritage of the Dane - even though there are now only a handful of brickworks left in the whole country.

The importance of the brick is due to its versatility - the brick has been adaptable and flexible in format and character to the changing of time but also to the human scale. And never without losing its tactile materiality. Maybe this is where the notion of quality comes in. The brick in itself does not secure architectural quality, of course, but there has been a tendency, in Denmark at least, to regard any building built in brick as possessing a certain quality.

Our office, Cubo, has always been in love with this quality of the brick and it has always been an important ingredient in our vocabulary. Maybe we grew up in different settings but always with the brickwork within the boundary of our separate neighborhoods. So the brick expresses normality, history and craftmanship, and some of the most beautiful Danish brick buildings do represent works of great Art. But as such an important element of our history it must be confronted with the times, new building techniques and programmatic issues like sustainability to maintain its appropriateness. Brick and sustainability usually brings frowns to life-cycle experts. But it has been my experience that the brick, in spite of the energy used in the making, has a lifespan that is ever so much more important because of the dedication and quality that it usually represent and therefore it is saved in buildings for generations on (if it's good architecture!) or it can be reused into other buildings and even in a crushed form it can find new use.

Figure 1-2:
Brickwork at University of Virginia. Photos by Lars Juel Thiis

When we discuss sustainability, we often find an eagerness to use rational and logic methods because sustainability must be measurable! Breem and DGNB tells the story of a general trend, in our society of today, to measure everything. Everything must be based on evidence - the quality of our work, the teaching in our schools, the maintenance in our surroundings and buildings, but also the quality of the buildings themselves? Architectural quality has been examined in numerous dissertations, and many have failed to construct architecture into measurable criteria. And they will never succeed. The beauty and power of architecture is typically derived in irrational circumstances, and, before I mention some of our own brick buildings, I would like to pin-point an example that has inspired us both in architectural competitions but also in our understanding of sustainability. This example is old but it still shows both the potential of good architecture, the potential of the brick and the potential of sustainability. And why, in 1820, sustainability was a normal procedure and why we have been going backwards ever since.

The Lawn

The president and author of the Declaration of Independence, Thomas Jefferson, designed University of Virginia in the United States with the aim to present the educational campus of the future. It was created in a neoclassical architectural language, very Palladian, and Virginia does resemble Tuscany in climate and topography. The brick is evident as the local building material, both in Italy and USA, although the Tuscan brick has links to ancient times as shown for example in Forum Romanum in Rome. Jefferson wanted to design a very democratic institution that had history and knowledge woven into the built environment, a life science campus that represented the world. Although the plan is strict and axial, it is softened by the impact of nature in the center – the great green Lawn, which is the spine of the whole campus and has become the structural generator for the whole campus.

The focus of the university is the source of learning, the library, which takes up the prominent situation on the axis, clearly being the center of attention. It's a Pantheon in miniature and from here the beautiful lawn reaches out into the landscape framed by low arcades. Each faculty is a satellite on the arcade with its own pavilion. Halls for teaching are below and the living quarters of the professors are upstairs. Each pavilion were detailed in an appropriate architectural style, Doric, Ionic or Corinthian and devirations of these – so the students learned about architectural history while they were studying the medicine or the law. In between the Faculties were the student dormitories, and the professor could visit his colleagues by strolling on top of the dormitories along the rooftops. Natures green is just outside the faculties and student lodgings, and The Lawn, now with large old trees, is terraced as an A-ha experience towards the horizon.

It is a beautiful university campus that has a universal aura to it, but it is also clearly rooted in the place and setting of Virginia. It shows the timelessnesss of the brick, but it also show some messages about sustainability. Actually, it is a minor, but beautiful detail that provides a distinct lesson for the future.

The approach to the Lawn and the pavilions of each the faculty was arranged from secondary streets lined with serpentine brick walls. These walls formed pleasant small gardens to the back of each faculty and the serpentine walls are the main issue of this example taken from the past.

When the university was being built cost was a problem. It was too expensive and somehow Jefferson and his architects had to find ways to save money. Jefferson insisted

Figure 3:
Aarhus School of Business. Photo by Martin Schubert

on bricks but each brick was dear. On the other hand it was local, and it turned out to be the cheapest material because transportation was expensive in the old days. They had to be very inventive and the serpentine walls show us this inventiveness.

Normally one would build brick walls in the depth of a whole brick for strength and stability but by curving and establishing the serpentine pattern Jefferson found out that it was possible to use just half a brick depth because the curves created the necessary static stability. So they saved both brick and money, they used the local material – and everything was very sustainable. And the most fruitfull quality that grew out of this inventiveness, was the beauty of the curved walls that formed niches and small protected spaces inside the gardens and also created a varied and spatially elegant street.

The university is alive and well today, nearly 200 years later, showing how sustainability and the brick together can form architectural quality through the use of inventiveness, local material and minimal but relevant design. This is an example of how all sustainable projects should be designed and constructed. That is, 2+2 can be 5.

Cubo belongs to the more pragmatic field of present architectural discourse, and the built examples addressed below are very pragmatic solutions involving the brick. They are educational and cultural buildings with limited budgets so it has been a difficult task to reach that certain level of quality. But the brick helps us in many ways.

Our buildings on the University Campus in Aarhus are heavily related to the historic context of the original project of Fisker, Stegmann and CF Møller from 1931. The University Campus is normally defined as an example of the Danish Functionalist Tradition expressing both a certain Nordic sensibility and an interpretation of the more stark functionalism of continental Europe. It is the brick that has woven a connection to history and inside the old Campus grammar it is vital to respect the master landscapeplan of C Th Sørensen. We do not know if the authors knew of Jefferson's Virginia but also here a great lawn ties everything together although the lawn is an integrated part of a larger park area into which brick buildings are situated in a horseshoe shape edging the valley.

Our addition to the Aarhus School of Business and Social Sciences is situated just outside the old campus and was originally designed by CF Møller i the 50'ties, and our approach was respectfully restrained. We arranged the new Multifunctional Entrance Hall parallel to the existing fabric, same heights and the same volume. It's in the detail that you experience the new. The gable, as the focal point of the many buildings on the Campus, was transformed to a transparent 'sign', an open faced brick wall, as a modern screen.

The theme of the gable is also developed in the Faculty of Health Biomedical research and science building inside the old Campus park. The oblong building volumes with pitched roofs are coupled together and at the junctions diagonal vistas glance through the perforated bricks gables.

In contrast, the Skejby buildings, outside of Aarhus, define their own 'tradition' in the interpretation of the Danish 'long house' – an old building typology. The brick is vital to the dialogue between these two buildings. It is a construction of opposites – it is a dark and a light building, it is two stories and one storey. It is confronting the street and it is set back.

The Vandhalla building in Hou, south of Aarhus, is a more expressive statement that responds to specific functional and contextual constraints. Varied roofscapes culminates

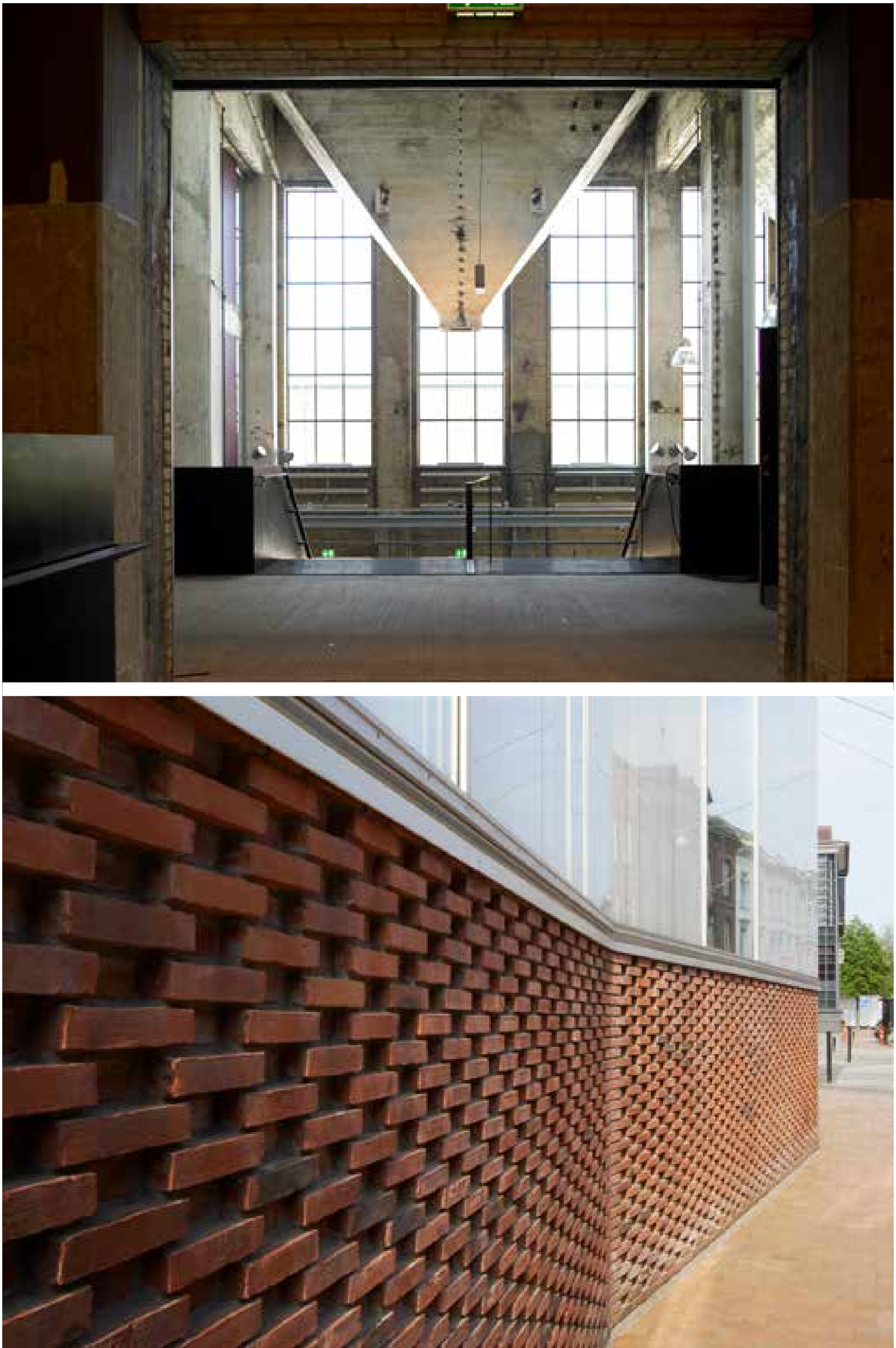


Figure 4-5:
Top: Nordkraft, Aalborg. Bottom: Odense High School. Photo by Martin Schubert

in this new addition, as the brick tower for the water basins forms a natural landmark both for the High School of Egmont but also for the small village of Hou.

In the extension of Odense High School the brickwork becomes the base for new material and acts as the connecting link to history. All the surroundings are red brick. Even the pavement is brick so it was the obvious choice to prescribe brick as the sole material. On the other hand, this site needed something different, something else and something more. A more profound gesture on the prominent corner site in the historic part of Odense, situated vis a vis the city theater, called for a reinterpretation of the identity of the educational institution. We defined a new volume on a built pile of bricks, a new transparent and more faceted composition that was both closed and open. Open on material, reflecting the surroundings and admitting sufficient daylight to the general classrooms both also closed in keeping with sustainable demands. The brick on the pavement is transformed into the base of this new building, an elevated parking garage.

The city of Aalborg in Northern Jutland is a former industrial town, and the power plant for all this industry has been abandoned like in so many other industrial centers. Nordkraft is now transformed to a cultural 'power plant' as its spans most of the cultural specter - cinema, music hall, theater, art gallery, leisure facilities, sport clubs, health centre and even the University has their faculty of Leisure here. Nordkraft still tells the story of the old Aalborg, the industrial town, because we are left with all the clues about its past. And there are also stories about bricks.

When we experienced the old buildings, we found out that all the bricks derived from brickworks on the island of Bornholm in the Baltic, and the flooring was either Hasle tiles, a brick tile, or Rønne granite, a very dark, almost black granite of great beauty. Nearly all materials were from this small island, somewhat remote from mainland Jutland. The quality to these surfaces oozes with history, and that was our main target – to keep history intact and alive. When they are confronted with new materials and fittings a certain positive quality occurs – historical layers become visible and active. Alas, to day all the brickworks and granite quarries that formed Nordkraft is closed. All the industry that ones gave the foundation for both the island of Bornholm and the city of Aalborg has gone. It's a paradox that in these sustainable days, we buy the granite in China and the closer you get to Denmark the more expensive granite gets - only because of the cheap labor and attractive freights rates.

We won't be able to address essential sustainable issues seriously before we realize that transportation in our building industry is to cheap. And the use of the brick, the local material, is not only one way of starting to make architecture more sustainable, but it is also a way of addressing the need for architectural quality. Architectural quality is the easiest way to secure that the building will be kept for generations, - as so beautifully evidenced by the nearly 200-years old University of Virginia.

Rethinking Brick

Kjeld Ghozati

Historically, brick and tile has been used for large and small buildings alike – everything from humble dwellings to magnificent cathedrals. Brick and tile was often the primary building material. For instance, we have many churches almost exclusively constructed in brick and tile. Buildings where brick and tile has been used for flooring, external and internal walls as well as arched ceilings and roofs. Over time, brick has changed from a 3D building material to being used primarily as a 2D facing material. The reason for this lies in new building techniques using steel, concrete and prefabricated elements, which open up new possibilities, shorten construction time, and lower costs, especially when building multi-storey. Undoubtedly, the receding use of brick and the failure to properly exploit its potential is also due to a lack of knowledge about building constructions, and about the particular tectonics and possibilities offered by brick. We must devise new building constructions using brick, and we need to learn how to use this material in a sculptural way. This is the task that lies ahead of us.

The age of variation and limited colours

Throughout centuries, most regions had tileries and brickyards. Individual regions frequently had their own specific brick format, with small variations in size compared to other regions. For a long time, the large medieval brick ('monk brick') was used, and this brick in particular is found in countless sizes. Bricks also varied greatly in size between themselves due to the processes of homogenisation of the clay and the firing of it not being as far advanced or controlled as they are today. Red clay and the typically deeper-lying blue clay – which produce red and yellow bricks, respectively – are found in many places in Denmark. The colour of bricks was almost exclusively red or yellow, with variations in shades between red and yellow as a result of the mixing of clays and

Figure 1:
FlexSystem by Egernsund Tegl – Danish Brickmakers
FlexSten (228x108x48mm), MunkeSten (228x108x78mm) & RomerSten (348x108x33mm)
Photo by Egernsund Tegl

the firing in coal-fired ring kilns, which could never be fully controlled. A lot of these naturally occurring shades are incredibly beautiful and enriching to architecture.

The age of Standardidation and many colours

From a time of many sizes, Denmark enters a period from the middle to the end of the eighteenth century where the so-called Danish Normal Format (DNF) bricks (Danske Normalsten) are almost exclusively used. DNF bricks measure 228x108x54 mm and are based on 6 cm modules width and lengthwise, whereas heightwise it has a different module, namely three bricks per 20 cm. With a few exceptions, such as the Flensburg and Kolumba formats, this is the format that was used almost exclusively for decades in new building works in Denmark. The format has been standardised, with the advantages that this entails, but interestingly the colour scheme has moved in the opposite direction, introducing an explosion in colour variation. Today, several hundred different shades are available, and methods such as engobing, reduction, fluxing using manganese and other aggregates, coal stinting, blue-brick firing techniques and foreign types of clay are frequently used. It seems that there is a great urge to stand out, in spite of the format now being standardised. This has produced neighbourhoods displaying a great variety of brick colours. However, several of the historic cities and towns that we find particularly beautiful, such as Siena, Assisi, many white greek towns and so on, are characterised by uniform colours. And then there are those that say that all towns are beautiful when it snows.

The age of configuration and fewer colours

In the old days, wages were a small part compared to the cost of materials. Today, masonry wages far outstrip the cost of materials. The outcome has been that where brick building used to be marked by many details, today it mostly seems void of details. Well-chosen masonry details, however, can help heighten the sense of quality in a building. So, it seems obvious to suggest that if building details are to be reintroduced, this has to be done in a fairly easy manner in order to expedite the building process as much as possible. Producing a brick based on a modular measurement of 6 cm length, width as well as heightwise – will introduce the possibility of turning over the brick at one's discretion, as measurements will always come right. Where the brick industry throughout history has had many sizes and many systems, a well-known toy manufacturing group has had great success with many sizes but only one system. This is the secret behind configuration – that things fit together, allowing the combination of different sizes, which makes for an endless number of new possibilities. One can imagine and hope that these new possibilities will give rise to enriching variations and stimulate building developments that are more uniform in colour.

The FlexBrick System - three sizes, one system

My fascination with configuration and my desire to discover more simple and financially viable ways of working with brick has led to inventing the FlexSystem (Figure 1). The FlexSystem is inspired by a well-known building system from the toy manufacturing industry, which has various sizes but only one system. The FlexSystem is based on applying the horizontal modular measurement of 6 cm to the height of the module as well. In this way, maximum flexibility in the use of the brick is ensured and it becomes a lot easier to work out measurements. A height of 18 cm comprises three FlexSten (228x108x48 mm), two monk bricks (MunkeSten - 228x108x78mm) or four Roman bricks (RomerSten - 348x108x33mm). Mortar joints are always 12 mm.

Figure 2-3:
Mengel Tower, Aarhus, E+N Architecture
Photos by Thomas Mølvig

Three examples of building

On the following pages, three projects are presented: a church, an urban block of flats and a house. These three projects illustrate my own trajectory in working with brick and configuration. A journey that began with a fascination for the possibilities in the reintroduction of details in clay brick expression, which translated into a desire to explore the textural options offered by brick and then into working with brick not only as a facing material but as a tectonic building component in a solid masonry project.

Brick as decoration FlexStone Church, Aarhus

The church hall (Figure 4) is an addition to a refurbished office building used by the parish as class rooms, offices and a coffee shop. The parish – belonging to the Danish National Church – presented the design studio with the task of building a church hall as large and inexpensively as possible. After casting the foundation, the entire church hall was erected in nine days, using concrete elements, including light, prefabricated roof elements. Subsequently, the church was closed and veneered. The church hall came in at a cost of approximately 40% less than a standard church building project, due to its raw aesthetics and quick construction time. As the first, larger building, the church is built in the brick format FlexStone. FlexStone is the name applied by Randers Tegl to the 228x108x48 mm format. The use of FlexStone manifests itself in several modulations in patterns in the clay brick facing of the church.

The two-storey interior of the church hall stands raw and plain with columns and beams, as well as floors and wall panels in raw concrete. The expression is modified by a rhythmic sub-division at the structural, horizontal concrete wall blocks as well as a gradual decrease in height of the longitudinal external walls. In its guide to architecture, the City of Aarhus praises the church hall for its expression of powerful poetry and a textural atmosphere through very simple means.

To secure the future of a church which boasts an innovative environment and increases in its congregation, the church hall was designed to allow for the addition of a glulam construction to create a first-floor balcony with 125 extra seats to supplement the 325 seats on the ground floor. The glulam addition was built in 2015.

Brick as texture Mengel Tower, Aarhus

The building (Figure 2-3) is a sculpturally designed block of flats with seven storeys and has been named ‘the world’s smallest high-rise in the world’s smallest big city’. The design of the tower has its origin in the trapezoid plot, which called for a unique solution. The building consists of several vertical wall blocks interspersed with windows from top to bottom. This gives the building a very vertical expression, which evokes associations of high-rise. The project is laid out as 15 modern flats with plenty of light. There are one-room, two-room and three-room flats, as well as a shared rooftop terrace on the penthouse level. At the back of the building facing west, large glass panels and private balconies afford views over the city.

This is the first building where the masonry has been done in a new and slimmer Roman brick (RomerSten) developed for the project during the planning phase. The advantage of this brick is that it is relatively inexpensive to buy and to use. This enables a very exclusive expression at modest additional costs. With its bond and slim clay bricks, the expression resembles that of a piece of woven textile. The masonry has several details, for instance protruding, laced brickwork at the corner junctions, and areas where twisted masonry distinctly catches the sunlight.

Figure 4-5:
FlexStone Church, Aarhus, Exners Tegnestue & E+N Architecture, Photo by Thomas Mølvig
Villa Octagon, Aarhus, Arinsto & E+N Architecture, Photo by E+N Architecture

Villa Octagon, Aarhus

The house (Figure 5) is situated on a previously unbuilt plot between historical, classic 1915-1930s houses ('murermestervillaer') predominantly in red brick. Villa Octagon is attuned to these adjacent houses through the continued use of red brick.

The centre of the house is occupied by an octagonal main room, the light-filled focus point of the house, which functions as a kitchen/dining/family room. The room has high ceilings and a light strip which ensures sunlight from all corners of the world. The main room leads on to all other functions of the house, which can be configured to suit the needs of the client. Two of the rooms in the house, the entrance hall and the morning lounge facing southeast, have facing masonry internally to give them the appearance of exterior rooms.

The back wall is built in monk brick (MunkeSten) and the front wall in Roman brick (RomerSten). There are two courses in the front wall for every one course in the back wall. The use of monk bricks (MunkeSten) in the back wall, which needs rendering anyhow, cuts down on costs, while a Roman brick (RomerSten) front wall gives a very exclusive expression at modest additional costs. This is the first house built in Roman brick (RomerSten), and the first project where the FlexSystem's monk brick (MunkeSten) has been used.

Summary

Brick is and always will be a building material with many advantages. It is a very durable product of nature, in many ways environmentally friendly, and not least a textural material which mellows alluringly. Brick has a number of advantages and qualities, rivalled by few other materials. So, we must reinvent brick as a building material and rediscover its sculptural potential. As Louis Kahn said, 'even a brick wants to be something'. As architects, we must help turn brick into something great and meaningful.

Robotic Brickwork: Towards a New Paradigm of the Automatic

Tobias Bonwetsch, Jan Willmann, Fabio Gramazio and Matthias Kohler

Abstract

This contribution characterises the fundamentals of robotic brickwork — where industrial robots are used not only for construction but also as a guiding principle in the design and fabrication process. Featuring six-axis robotic arms that position single bricks according to a precise digital blueprint, robotic brickwork offers a comprehensive new paradigm in building construction: intricate automated assembly methods. Initiated by the Gramazio Kohler Research Group at ETH Zurich, this approach to brickwork offers unique advantages over traditional brickwork approaches: it does not require scaffolding, it is easily scalable and it offers digital integration and informational oversight across the entire design and building process. This contribution considers 1) the advent of robotic brickwork in architecture, 2) research parameters and demonstrations for integrative computational design methodologies and fabrication techniques to enable this process and 3) the architectural implications of integrating these components into a systemic, unifying brickwork construction system. Industrial transfer and full-scale construction are of particular concern.

Automated Brick Assembly

In robotic brickwork, the combination of a well-established building material, new digital design processes and fabrication techniques allows non-standard assembly to become an increasingly interesting architectural avenue, departing from traditional and labour-intensive manufacturing processes. Indeed, despite strong advancements in digital planning using computer-aided design (CAD) systems, the construction sector is still characterised by a high proportion of manual assembly tasks. Together with the inherently limited flexibility and working areas of conventional computer numeric control (CNC) machinery, this handicaps the field with regards to taking

Figure 1-2:
In 2005, the Gramazio Kohler Research Group installed the first robotic laboratory (top) for non-standard automated fabrication processes in architecture; (Bottom) early approach to robotic fabrication of a non-standard brick wall. Image copyright Gramazio Kohler Research, ETH Zurich, 2005/2006.

advantage of the rapidly spreading trend of using complex digital design information directly as input for comprehensively automated construction processes. Here, robotic systems are extremely useful: not only can their use lead to significant time savings but their ability to precisely transfer computational design data directly to real-world manufacturing operations can also enable the fully automated construction of non-standard building structures. In particular, their use opens up entirely new possibilities for future brickwork that is not limited by the same constraints — such as, for example, standardised assembly routines — that limit manual assembly processes; its most evident and radical consequences are the ability to digitally oversee and control a large number of elements and, most importantly, the ability to freely position these elements in space. In order to address these potentials, the Gramazio Kohler Research Group at ETH Zurich started comprehensive investigations into robotic brickwork (Figure 1) in 2006 and created a number of architectural demonstrations and building prototypes. These explorations are an important step away from standard brickwork towards enabling highly articulated building elements, where both a novel aesthetic and a functional potential are liberated through the introduction of bespoke assembly operations (Gramazio and Kohler, 2008a). Because the resulting artefacts are robotically constructed, the resulting structures combine the flexibility of individually fabricated, highly customised building parts with the advantages of additive mass production. As such, these brickwork elements can be fabricated without any need for repetition, at low cost and with a constant and controllable quality. The driving force behind this approach is not the mere rationalisation of fabrication as pursued by former approaches during the 1990s (Andres et al., 1994; Pritschow et al., 1994), but the exploration of novel brickwork constructions and their relation to design freedom, structural performance and the robotic assembly itself.

This unique approach to robotic brickwork is particularly explored in projects such as the Gantenbein Vineyard Façade (Bonwetsch, 2015) and the installation Structural Oscillations (Gramazio and Kohler, 2008b), which are presented in the first part of this contribution. Subsequently, we will discuss the industrial transfer of this research to large-scale demonstrations, namely the software tool BrickDesign (Bonwetsch et al., 2012) and its application to the design and fabrication of the façades of the multi-residential building ensemble Le Stelle in Locarno, Switzerland. All these endeavours required many innovations (including the development of novel computational design and construction processes, interfacing seamlessly with automated fabrication procedures) and successfully illustrates the potential of comprehensively automated brickwork assembly processes, fostering profound changes in the design, performance and expression of architecture at building scale.

As shown by the projects discussed in this article, robot-based construction processes are usually distinguished by the large number of elements, very detailed organisation, high degree of definition throughout and a distinctive coherence between the single elements and the whole. Nevertheless, the prospect of using a robot to join simple, basic elements into a complex whole calls for a short discussion of the concept of the 'generic' building element (Gramazio et al., 2014). A brick is fundamentally generic because it can be assembled in a number of configurations resulting in very complex and specific building elements. One could also say that although its form is geometrically clearly defined, its assembly logic is weakly determined. In the joining of the bricks, their formal

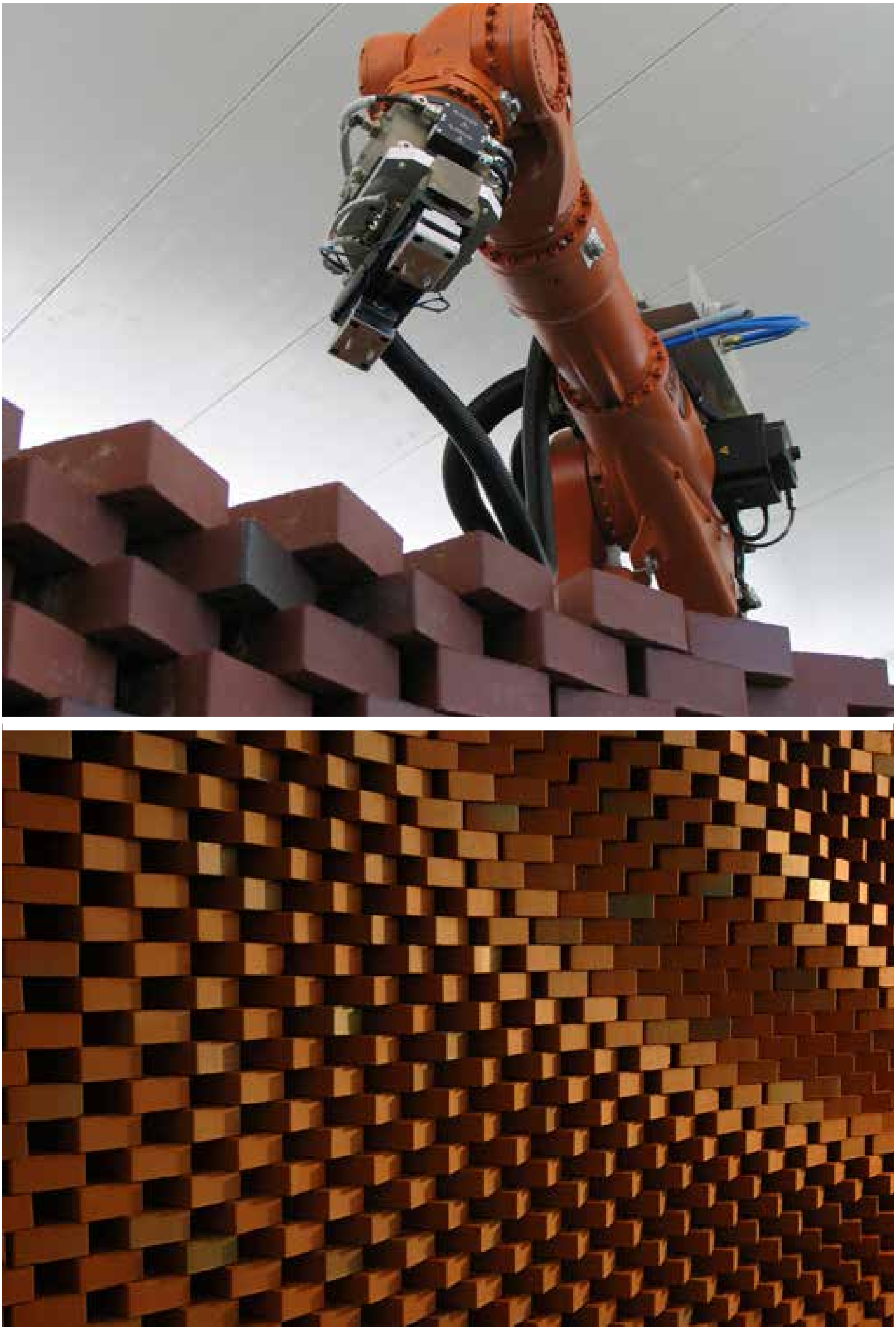


Figure 3-4:
View of robotic end-effector during assembly; (top) detail view of a dry-stacked automatically fabricated brick wall.
Image copyright Gramazio Kohler Research, ETH Zurich, 2006.

simplicity allows an enormous degree of freedom — for example, highly articulated and continuous translations or rotations that would not be possible with a building element that constrains the freedom of assembly through a specific form (Figure 2).

The boundaries of this freedom, however, are clearly defined and are all of a physical nature, such as collision, tipping or tilting during the construction process as well as the structural bonding effect among the bricks. In addition, the complexity of the constructive logic increases dramatically as soon as one departs from the rich canon of traditional bonds. This complexity, generated by the diverse dependencies between the single bricks, can be designed and controlled only through algorithms. Whether the brick — today, in the information age — can still be 'glorified' as the lowest common denominator of architecture may well be doubted. But one thing is certain: To this day, the brick remains the most 'generic' building element of construction — also and especially in digital fabrication with a robot. With regards to assembly, to the extent to which generic elements can be put together into various, highly informed and differentiated architectural assemblages, the application of robotic assembly techniques becomes not only meaningful but indispensable. Conversely, as soon as the individual elements become specific through geometrically prescribed connections, their joining is largely predetermined and constructive freedom becomes limited. The consequence is that sometimes such elements may be put together more easily and perhaps more quickly by hand than with the robot; in these cases, the specific added value of the robot would be reduced to the pure automation of manual work processes.

At the same time, on a technical level, brickwork lends itself particular well to robotic processing, especially as industrial robots were developed mainly for performing handling and assembly tasks and the basic construction process of brickwork consists of the repetitive assembly of discrete parts. The parts assembled are mainly of the same size and material and are of dimension and weight that can easily be handled by a robot (Figure 2). Further, in traditional brickwork, the bricks are merely stacked on top of each other. Thus, the robot is not challenged to assemble complex joints. In fact, the constructive brickwork system developed and presented here substitutes the traditional mortar bond with an adhesive. On one hand, applying adhesive corresponds to automated robotic processing and is a well-known technique in other manufacturing industries such as, for example, the automobile industry. On the other hand, bonding bricks with an adhesive adds a new performance quality to brickwork, in that it can now receive tension forces. Thereby, as shown especially in the Structural Oscillation project, we can realize complex geometries in brickwork structures which otherwise would not be possible or would be possible only through introduction of additional reinforcement (Figure 3-4).

Viewed from this perspective, it becomes clearer why brickwork is a research field par excellence for digital fabrication. In such endeavours, two aspects converge: the inherent 'genericness' of the elements used and the generic machinic capabilities of the robot. These are combined to enable specific and differentiated constructive processes that profoundly affect the architectural design and at the same time become thoroughly informed by it (Bonwetsch et al., 2010).

Figure 5-7:
Top: View of installation Structural Oscillations at the 2008 Venice Architecture Biennial. Image copyright Alessandra Bello, 2008. Center: Detail view of the Gantenbein Vineyard Façade; Bottom: Inside view. Image copyright Gramazio Kohler Research, ETH Zurich, 2006.

A project that precisely illustrates this approach and has expressed its potential from early on is the Gantenbein Vineyard Façade. This project is pivotal for two reasons: first, it marks a historic break as the first-time architectural application of an industrial robot. Associated with that is the transition from a manually repetitive to a digitally differentiated robotic fabrication process. The brickwork of this façade (Figure 6-7), in which each brick has been individually positioned and aligned, cannot be built by hand: its design is too differentiated; the bricklaying logic of the façade — that is, the highly articulated arrangement of the bricks, their offsets and angles — is too complex. Ultimately, its logic is not intuitively comprehensible to the worker during the act of bricklaying. Second, the Gantenbein Vineyard Façade is significant because it points to the question of how digital design can address the architectural capacities made accessible by the robot. The constructive and phenomenological relationship between resolution and transparency, between the brickwork and its visual appearance (Figure 6), between information and material must be brought to equilibrium among a multitude of diverse aesthetic and functional requirements. While such complex materialisation processes cannot be addressed with traditional design methods, they become controllable and freely formable through the medium of computer programming. This inaugurates an entirely new architectural approach that allows for bringing the discipline's fundamental material capacities into equilibrium.

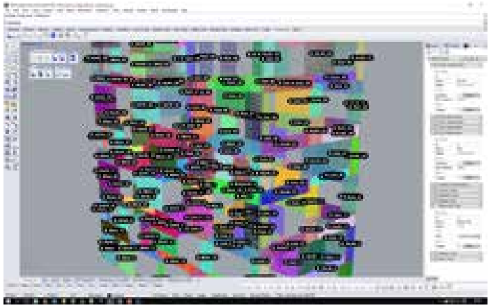
Besides the direct relationship between design and material, programming and construction, the question of the relation of the machine to the entire structure arises. Following the known paradigm of prefabrication, robot and building are initially spatially separated. If instead the entire robotic unit is made transportable — as with the mobile robotic unit R-O-B, which was put into operation for the production of Structural Oscillations, Venice 2008 (Figure 8), or Pike Loop, New York 2009 — then the situation changes considerably. In such cases, the robot leaves the protected surroundings of the factory and produces directly on the construction site. R-O-B stands for the flexible use of the robot and definitively expands the traditional prefabrication paradigm of the building industry. Housed in a modified standard freight container, the mobile fabrication unit can be deployed all over the world. R-O-B combines the advantages of robot fabrication — manufacturing diversity with consistent precision and production quality — with the advantages of short transport distances and the flexibility of production on the construction site. Thereby we return to the concept of the field factory, which was developed in industrial construction during the 1960s (Langenberg, 2009). The small factories for the serial production of building components that were erected directly on site for large construction projects could not gain a foothold because of the success of industrial prefabrication, which rapidly led to a dense network of factories turning out ready-made components. This resulted in considerably shorter transport distances to the respective construction sites, rendering field factories unprofitable. Today, with R-O-B, a reconceptualisation of this idea appears to be taking place, this time with entirely new possibilities for flexible production, whereby versatile construction procedures can be coordinated with the requirements of the construction site, just-in-time, and industrial quality. In other words, R-O-B is the core of a generic and information-based, and therefore flexible, new edition of the field factory.

Figure 8:
Mobile construction unit R-O-B, while producing bespoke brickwork elements directly on site for the installation Structural Oscillations at the 2008 Venice Architecture Biennial. Image copyright Gramazio Kohler Research, ETH Zurich, 2008.

Along with the robotic fabrication process, corresponding digital design tools that allow for truly integrated design and fabrication of robotically assembled brickwork are requisite for the successful transfer of this research to the building industry. Due to their limitations in designing with a large number of elements, traditional CAD systems do not qualify as design tools for robotic brickwork processes. In fact, the robotic assembly process demands new design tools. The software tool BrickDesign was developed to address this shortcoming (Bonwetsch et al., 2012). Conceptually, the software is based on the creative control of a large number of units in order to foster a systemic, unifying planning process. In this, BrickDesign allows designing a façade from its constituent elements — the bricks — rather than through an overall geometry (Figure 9). Thereby, the software enables exploration of the full design space spanned by the possibilities of robotic assembly processes. Further, the same data set for the design of the façade can be utilized for execution planning, such as panelising the façade and defining constructive details like anchoring points. Finally, the BrickDesign data is the basis for generating the control-code for the robotic system (Figure 9). In this way, the software combines digital design and fabrication into a computational planning tool and implements the non-standard robotic assembly process for brickwork in an integrated architectural planning process. By extending architectural planning and manufacturing methods, BrickDesign creates a new level of robotic use in architecture (Willmann et al., 2012).

A specific case for the industrial implementation of robotic brickwork is presented by the façades of the multi-residential building ensemble Le Stelle. The brick façades are based on an open stretcher bond, although the individual bricks move out of the two-dimensional plane of the façade, creating bossage-like protrusions that are irregularly distributed over the façades (Figure 10). The 3.425 square metre large façade consists of 87.382 bricks and was produced in 707 single non-standard brick panel elements. Like the previous realised experimental projects, due to the number of bricks that need to be individually controlled and the complex relation of their assembly, this façade could not be designed, planned or executed using conventional manual methods. From the early design stage, the façade variants were explored in BrickDesign. The complete planning, up to generating the fabrication data, was handled within the software, thereby realising a digital chain linking the design with the assembly process. Apart from allowing development of the design and execution details in parallel, such an integrated approach allows for a bi-directional information flow. Design and execution are synchronised by controlling each individual brick and assessing brick assemblies both in terms of their visual appearance and their feasibility, such as the maximum protrusion of the individual bricks according to the constraint of a minimum area of overlap between the bricks. Thereby, the design is combined with fabrication thinking, where function and form are negotiated in an informed assembly process. The brickwork is developed out of the logic of its material, construction principles and the tools applied. Ultimately, this holds the potential to leverage new architectural capacities outside the commonly known standards.

Figure 9:
(left) Screenshots of BrickDesign software illustrating a custom, three-dimensional façade design; (right top) elementing function to divide the façade into panels and set anchors for execution design; (right bottom) compiling batches of façade panels for robotic assembly. Image copyright ROB Technologies AG, 2012.



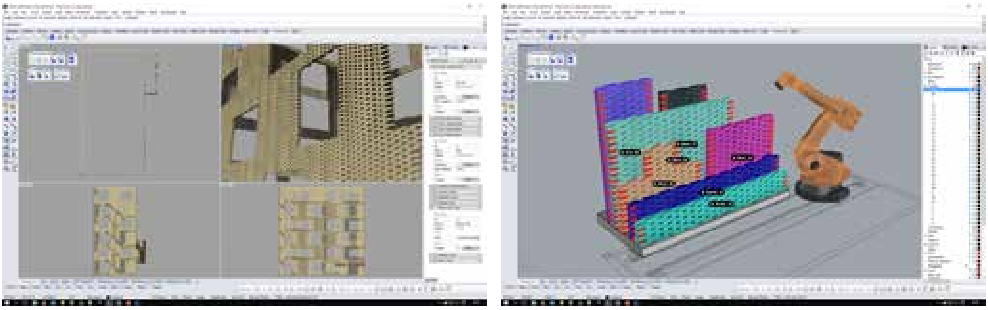


Figure 10:
View of the Le Stelle brickwork facades. Image copyright Marcelo Villada, 2015.

In the last decade, a number of promising robotic brickwork processes have been developed, resulting in robust and versatile brickwork constructions. Seen against this background, robotic brickwork has become a mature technology over the last decade, and, overall, has successfully brought forward the topic of digital fabrication as a new field of research in architecture. At the same time, this approach radically expands the spectrum of traditional brickwork and, additionally, introduces robotic fabrication logics to the building construction sector. Therefore, the presented explorations — spanning almost a decade of comprehensive research — represent a radical shift in scale and scope, where non-standard brickwork can be efficiently aggregated from a multitude of discrete elements to foster highly versatile constructions. Here, the realised projects make clear that even the oldest and most tradition-rich prefabricated building element, the brick, cannot elude processing by digital technologies; accordingly, this endeavour also promotes integrative computational design methodologies and techniques, where design decisions orchestrate a multitude of construction and fabrication attributes from the very beginning of the design process onward and up to the different stages of prototyping and final realisation. In order to fully exploit the potentials inherent to a robotic assembly process, its parameters have to be made available at an early design stage. Thereby, parameters of fabrication can inform the process of design exploration. However, the industrial transfer of robotic brickwork is still in its infancy and presents many challenges to architecture and the construction industry. And yet this approach is captivating: It not only creates a new vision for robotic construction in architecture but also emphasises new possibilities for the exploration of its real-world implementation — revitalising architecture's constructive nature and engaging with its own material roots.

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Synthesizing a Nonlinear Modelling Pipeline for the Design of Masonry Arch Networks

Anders Holden Deleuran

In architectural design, modelling is the primary method of generating designs. This includes models such as diagrams, plan drawings, physical scale models or building information modelling (BIM). In the sciences, modelling is an analytical discipline undertaken to investigate unknown problems or to predict the behaviours of known phenomena. The implementation of such models is referred to as simulation. Frazer (1995) has described this generative–analytical duality as the design model emerging from an assumed context, implying that a design model is always an abstraction of some scale and subset of reality. When engaging in design modelling, this necessitates a synthesis of the design space and the intended performance space of the design object. Modelling is thus both an analytical and a generative discipline defined by a design context, modelling language and domain of application.

A complex system is defined as one that consists of many different and interacting parts. A design process seldom requires only one model, but rather requires multiple disparate models interfaced in larger modelling infrastructures. When dealing with a network of interacting models, complexity may increase and become disruptive. In computational design, modelling complexity is inherent to the process of developing a model, as suggested by Dijkstra, who famously stated that “the art of programming is the art of organizing complexity, of mastering multitude and avoiding its bastard chaos as effectively as possible” (Dijkstra, 1970). Johnson states that complexity science “can be seen as the study of the phenomena which emerge from a collection of interacting objects” (Johnson, 2010). This is intrinsically linked to the modelling of phenomena and design problems that are inherently complex. The concept of modelling behaviour implies the abstract principle of agency: the capacity of autonomous entities to act in

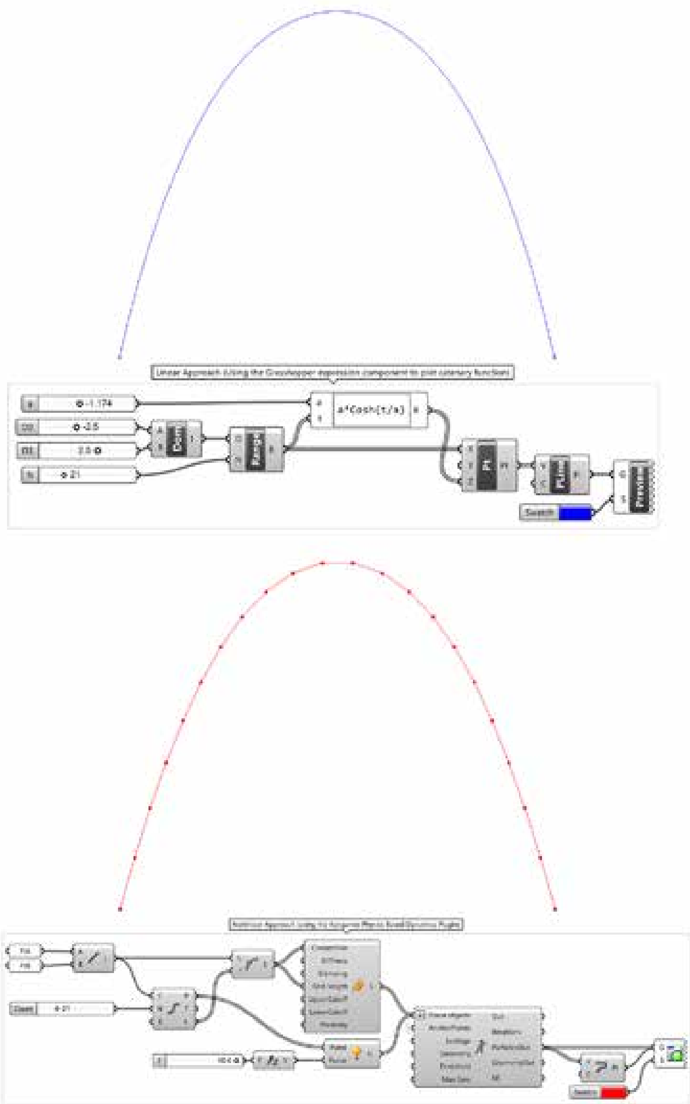


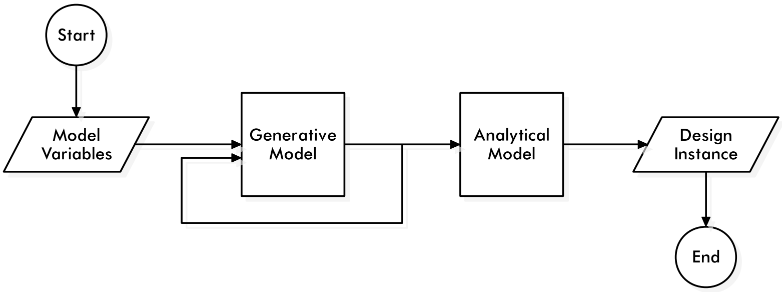
Figure 1:
Top: The catenary curve modelled using a directly solvable mathematical expression describing its overall shape. Bottom: The catenary curve modelled using a distributed approach in which we model local physical behaviour as a set of discrete springs and iteratively apply a global gravity force to these.

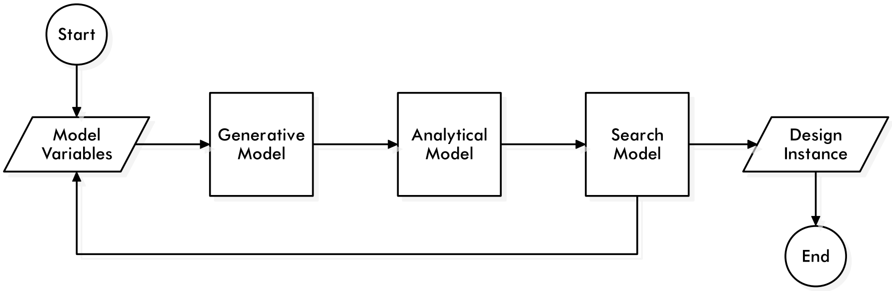
response to stimulus from themselves or their environment. This is what Coates (2010) referred to as distributed representation, and it is fundamental to the idea of bottom-up computational design processes. The development, synthesis and integration of complex models are thus an inherent challenge in computational design.

Computerized design processes use the computer as an extension of methods that might be performed using analogue methods; therefore, computerized processes fail to exploit the potential for iteration and logical modelling in solving complex design problems (Terzidis, 2006). Computational design processes may be defined as those utilizing computational methods. Computation is defined here as the process of applying an algorithm to an input to obtain an output using a modern computer. This implies the explicit definition of algorithms, step-by-step procedures designed to solve a problem or accomplish a task and their practical implementation in a computer program. In software development, this occurs in a process that leads from formulation of a problem to an executable computer program. When developed in response to a given design problem, such a program and its constituent components are defined here as a computational design model.

Woodbury (2010) describes the fundamental difference between computational design modelling and traditional design modelling as the introduction of design marks and a method for describing and updating the relation of these marks to each other. While there are many approaches to solving relational constraints, the one most commonly implemented in computational design environments used in architectural design is the graph propagation-based approach. A graph is an abstract construct consisting of nodes wherein some pairs of nodes are connected by edges. The designer defines design marks as node properties and further defines how they relate to each other as edges. To solve the constraints defined by the modelling graph, data are allowed to propagate through the graph network from one node to the next. Aish and Woodbury describe the use of graph-based modellers as a process in which "designers work in such systems at two levels: definition of schemata and constraints; and search within a schema collection for meaningful instances" (Aish & Woodbury 2005). The graph is thus a modelling language in which to define a design algorithm based on dataflow, which enables designers to explore many design instances within the same constrained design space.

When the edges of a graph have a direction associated with them, the graph is said to be a directed acyclic graph (DAG). This is the fundamental data structure upon which popular computer-aided design (CAD) modelling environments such as McNeel's Grasshopper®, Bentley's GenerativeComponents® and Autodesk's Dynamo® are based. As a programming paradigm, this mode of implementing algorithms is known as dataflow or declarative programming. This involves "stating what is to be computed, but not necessarily, how it is to be computed. Equivalently, in the terminology of Kowalski's equation algorithm = logic + control, it involves stating the logic of an algorithm, but not necessarily the control" (Lloyd, 1994). Woodbury points out that this has "the relative advantage of reliability, speed and clarity and is used in spreadsheets, dataflow programming and computer-aided design due to the efficiency of its algorithms and simplicity of the decision-making required of the user" (Woodbury, 2010). This simplicity, however, exacts a cost. The acyclic property of the DAG implies that it does not contain nodes that connect back to themselves via a closed cycle. Cycles have the effect that a child node can become its own parent, making it difficult for the DAG to





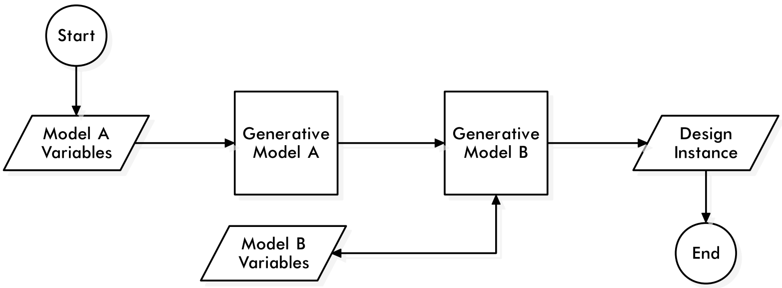


Figure 2:
A nonlinear two-stage modelling pipeline in which the generative sub-model is cyclically coupled with itself, thereby enabling feedback loops and recursion to occur on the local software architecture level.

Figure 3:
A nonlinear three-stage modelling pipeline in which the search sub-model has a feedback connection that allows it to refine the model variables of the generative sub-model, thereby enabling an optimization feedback loop to occur on the global software architecture level.

Figure 4:
A basic example of a nonlinear adaptive pipeline. If the output of Generative Model A changes its topology, Generative Model B will automatically detect this and update its own model variables list to accommodate the change in phase-space topology.

sort the nodes and deduce the control flow. This makes DAG modelling ill-suited for implementing the feedback loops and iterative algorithms that are essential to modelling complex nonlinear phenomena.

There are workarounds for this shortcoming. However, they typically work against the very principals of declarative programming as described by Lloyd. Imperative languages conversely describe computation in terms of statements that change the program state. Here algorithms are defined by explicitly expressing the control flow using the three basic mechanisms of Turing-complete programming languages: loops, conditional statements and data storage. A computer running such a language is theoretically capable of executing any computable process given enough time and memory (Downey, 2012). This paradigm includes popular textual languages such as C++, C#, Java, Python and Ruby. The CAD environments mentioned above all support one or more imperative languages. Developing a computational model is therefore not a question of selecting one programming paradigm over another but more a case of selecting the right language for the task and balancing and synthesising the two programming paradigms.

A physical system that has the characteristic that it can be directly expressed or solved using an iterative distributed model is the catenary curve: the shape assumed by an idealized hanging chain under its own weight due to gravity when anchored at its ends. This system, when turned upside down, will yield the ideal form of an arch working in compression. This curve can be described by a mathematical expression that allows us to plot points on it independently of the other points on the curve. However using this expression would allow us to model just that, the idealized hanging chain. That is, a simple non-interacting system where each element exists in isolation from the others. If we are to model more complex systems of interacting objects, or systems that have no known equations for their global shape, we will need to model their intrinsic behaviour and not their shape.

For a catenary curve, this could be achieved by modelling a discrete version of the curve, where each segment is a Hooke's law spring and each point between two springs is a particle, which is iteratively subjected to a gravity load. This process is referred to as a form-finding model. In Grasshopper, this could be modelled using the Kangaroo physics-based dynamics solver. Here, the interacting agents are the discrete curve segments of the chain and their behaviour is the product of cyclical subjection to a gravity load, causing the system to self-organize and eventually reach equilibrium. This system is characterized by a circular cause-and-effect sequence of events which form a feedback loop. This means that the output of the model is fed back into itself at each iteration, which we know is difficult using a DAG model. The Kangaroo solver gets around this by implementing its logic in an imperative language and using what is known as static variables. These are variables whose lifetimes exist outside of the scope of the program once created, thereby enabling us to circumvent the acyclic dataflow.

The catenary model is an example of a computational design model developed for solving an isolated task within its own separate algorithmic logic. As previously described, models rarely exist in isolation. For instance, where did the input curves come from and what happens to the form-found catenary curve? In practice, we manage complex design problems by networking multiple models in larger modelling pipelines. In computer science, a pipeline is a collection of data processing components connected

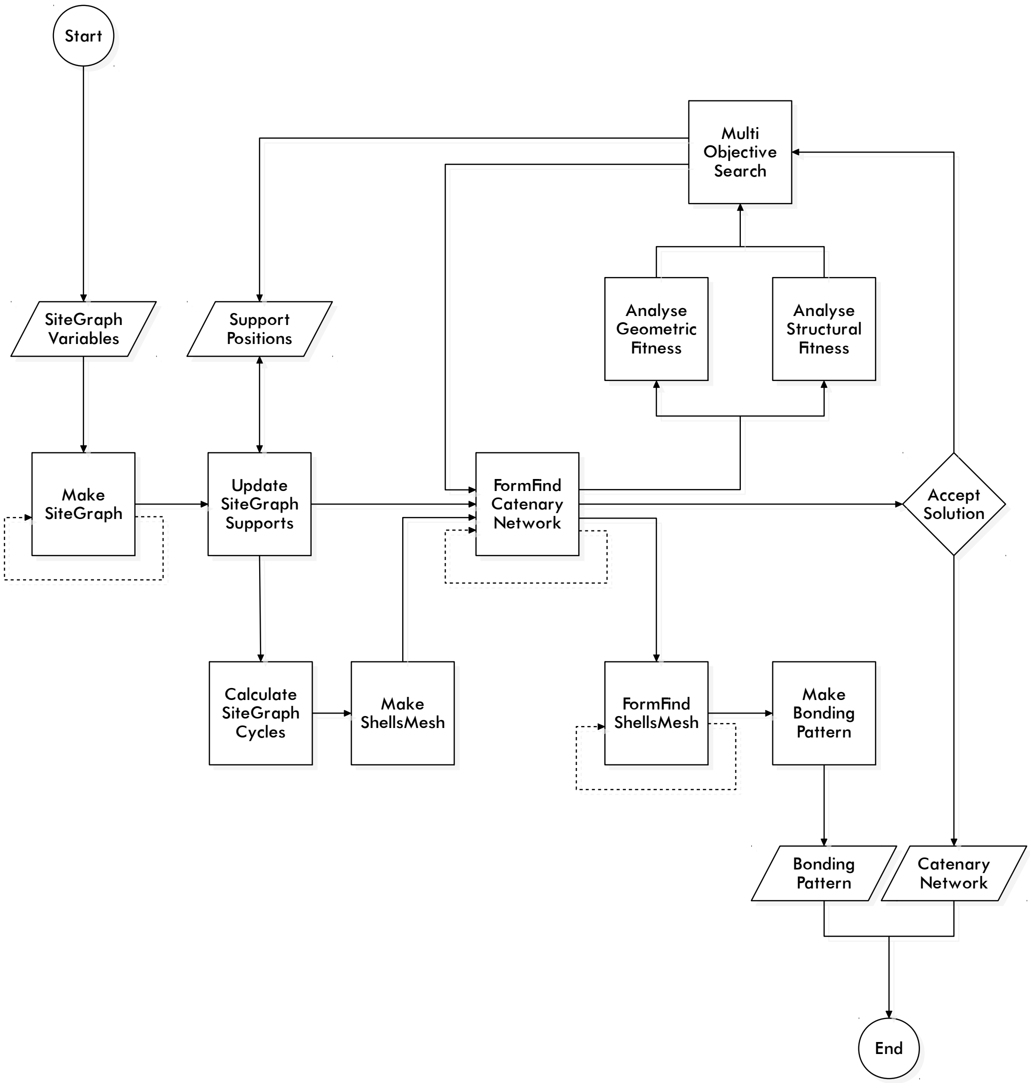


Figure 5:
Flowchart of the full modelling pipeline. This is developed as one Grasshopper definition with ten components and twenty points of user interaction. The pipeline has three local feedback loops, two global feedback loops and one bidirectional connection. Dashed feedback connections imply that iterations are solved statically within the local scope of the model.

in series, where the output of one component is the input of the next one (Lott, 2010). Though such pipelines may be fully parametrically defined, the level of feedback is still limited to a simple loop in which a designer manipulates the pipeline input by reacting linearly to the pipeline output. Negroponte suggested an alternative to this in which the designer instead engages the computer in a form of dialogue where “the design process, considered as evolutionary, can be presented to a machine also considered as evolutionary, and a mutual training, resilience, and growth can be developed” (Negroponte 1970). To enable such design processes, the pipeline must support both local and global feedback connections. When a pipeline has “feedback connections in addition to the streamline connections”, it is called a nonlinear pipeline (Godse & Godse, 2006).

The input data of a computational design model likely contains a list of numerical values defined within a range. These numbers are called model variables or parameters. While there may be many other types of input data, these values are typically the entry point nodes a designer uses to interface with a modelling pipeline. When Aish and Woodbury use the word instance, they are referring to both a design instance — that is, a design generated by the model — and the particular instance state of the variables list that parametrically defined the design instance. Each unique combination of data values in the variables list is thus equivalent to a unique design instance. If we consider all possible combinations of values in the variables list, this set is referred to as the design space of the model. When changing the variable values and thereby constructing new model states, the designer is said to be searching the model design space. A primary purpose of developing nonlinear modelling pipelines is thus that it enables the designer to interactively engage in a dialogue with complex self-organizing design systems and to find meaningful design instances within the design space delineated by the modelling pipeline. Meaningful is understood both in the sense that a design instance may be intuitively pleasing to the designer but also, perhaps more importantly, in the sense that the modelling system is inherently meaningful to the design task by its programmed behaviour. In extension of that, the pipeline may integrate analytical models which provide feedback to both the system and the designer in order to steer them towards increasingly more meaningful design instances.

These design systems are equivalent to what Kilian refers to as design explorers: “a physical or computational construct that combines design representations and constraints in order to support design exploration within the defined conditions” (Kilian, 2006). Kilian defines three approaches to computational design exploration: parallel, circular and branching. These refer respectively to exercising constraints interactively, refining a set of known constraint relationships and establishing constraint relationships in the first place. In reference to the previous sections, these three approaches are equivalent to iteratively modelling nonlinear phenomena, searching the design space and developing the modelling pipeline. While Kilian refers explicitly to only one of these approaches as being circular, they are all processes that are dependent on establishing and managing feedback mechanisms in the modelling pipeline.

When a model is locally coupled to itself, it becomes possible to iteratively model complex nonlinear systems and for the designer to interactively engage with the behaviour of the system by changing its input model variables. This interaction can be implemented in two different ways: the node continuously updates and the model

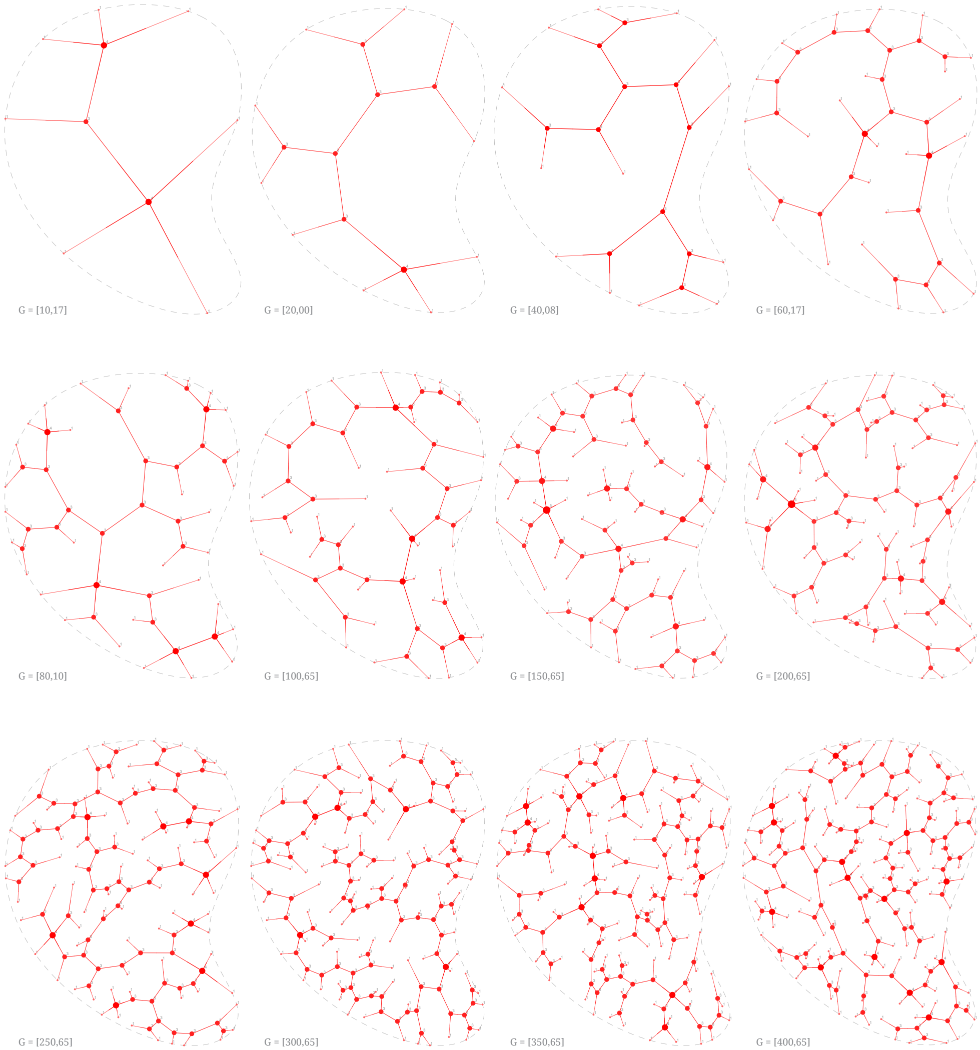


Figure 6:
Twelve site networks generated using MakeSiteGraph. The nodes are coloured and scaled according to their valence. Even large numbers of nodes yield a network that satisfies the design criteria.
G= [NodeCount, RandomSeed].

outputs its current solution at each iteration, or the node updates only once and outputs its solution after a fixed amount of iterations or when some condition has been met. In the case of our catenary chain, the first implementation allows the designer to interact directly with the behaviour of the form-finding system. The second implementation allows the designer to evaluate the form-found solution directly in its state of equilibrium. The former is better for understanding and refining the system and the form-finding process. The latter is better for searching the design space and quickly iterating on design instances.

Depending on the definition of the design problem, the design space may be very large in terms of both dimensions and range. This can make it difficult to navigate and it may become impractical for a human to perform an exhaustive design search. However, if an analytical model can evaluate the meaningfulness of a design instance by assigning it a numeric score, we can integrate models known as generic solvers in the modelling pipeline. These have the capacity to computationally perform an exhaustive search of the design space and find meaningful instances on our behalf. More formally, this involves defining the design space delineated by the amount and range of model variables as being the phase space of the model and the numeric value defining meaningfulness as being an expression of the fitness of a design instance (Rutten, 2014). This process is referred to as mathematical optimization and is described as a problem of finding the best candidate, with regard to some criteria, from a set of potential alternatives. In the case of our catenary chain, such a pipeline could be used to determine, for instance, the exact length of chain needed for the resulting compressive arch to have a desired height.

It can require a substantial effort to define the phase space and fitness function due to the problematic nature of formally defining what constitutes a meaningful design instance unless the problem is already well defined and, in extension, which constraints and parameters are the most important to making it meaningful while still allowing for generating design variation. Davis (2013) refers to this challenge as a product of an inherent inflexibility of computational design modelling which will often result in having to redevelop the model from scratch if design changes become too disruptive and cause the model to lose its meaning to the project or if it simply begins to unravel. This implies that it is problematic to alter the topology of the design instances without also altering the modelling pipeline itself. The design space search is therefore often limited to exploring metric variations of a fixed design instance topology.

Harding (2012) suggests that an approach to meeting this challenge is to give the modelling pipeline the autonomy to dynamically change itself. In computer science, this concept of a program that can modify itself is known as metaprogramming. This could be implemented in design search for at least three purposes: to automatically generate modelling pipelines, to automatically adapt to changes in existing modelling pipelines and to listen to and trigger events in the modelling pipeline. The first proposal is quite radical and is similar to what is known as genetic programming. This concept essentially involves using an evolutionary generic solver to search for computer programs that can perform a defined task, that is, developing a program that develops computational design models. The second and third proposals are substantially less radical and involve enabling the nodes in a pipeline to react to changes and manipulate both the pipeline and the other nodes.

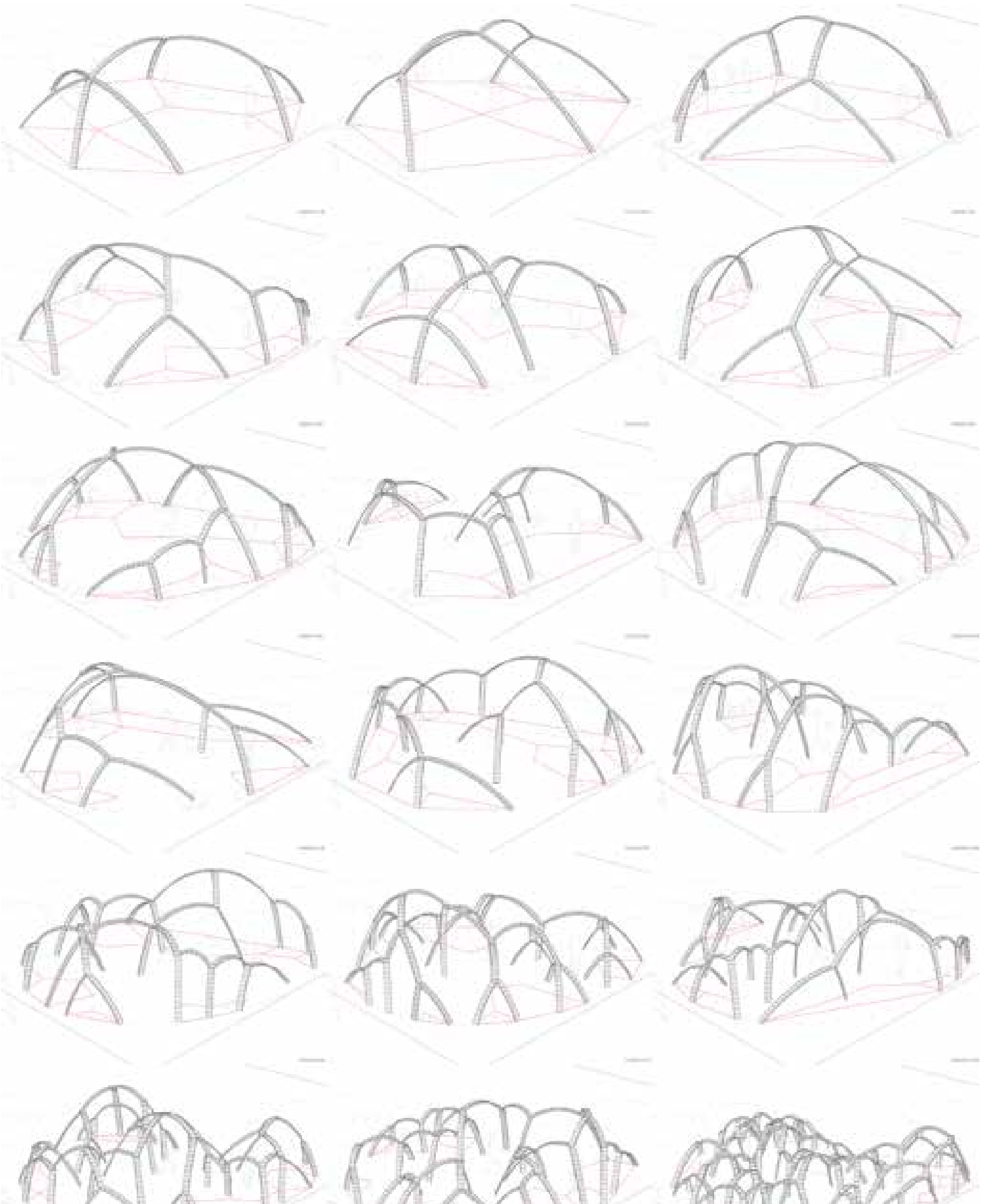


Figure 7:
Eighteen catenary arch networks form-found using FormFindCatenaryNetwork. The red polygons are the initial shell polygons. G= [NodeCount, RandomSeed, GravityMagnitude].

To exemplify the theoretical topics presented in the previous sections, the following sections present the results of the author's work conducted as a participant in the UtzonX 2014 summer school. The pavilion design concept was developed in collaboration with David Stasiuk.

The concept is based on a primary structural system consisting of a network of form-found catenary masonry arches. To generate enclosure, a second system is added between the arches in the form of brickwork shells. This is similar to the design principle famously implemented by Gaudi with analogue models for form-finding the complex compressive vaults of the Sagrada Familia. This modelling principle has also previously been implemented in computational form-finding by Kilian and Ochsendorf (2005) and Sunguroglu Hensel and Bover (2013). The primary aim of the research presented here was to synthesise a nonlinear modelling pipeline that would enable us to explore topological diversity of the catenary arch network typology. Specifically, this included answering the following questions:

- How do we model the initial network?
- How do we implement a catenary form-finding model?
- How to we define meaningful fitness criteria?
- How do we implement a multi-objective search solver?
- How do we model the infill shells?

After deciding on the catenary arch network typology as the principal design concept, the need for formalizing the geometric characteristics of the network presented itself. It quickly became apparent that minimising the number of arches meeting in a node is a primary constraint. That is, a low network node valence must be maintained. With the goal of exploring topological diversity, a generative model was required. The algorithm developed for this was encapsulated in the MakeSiteGraph component. The input for the component is a closed curve delineating the area within which the pavilion should be contained, an initial node count and a random seed. The modelling algorithm is divided into a pipeline with four processes:

1. Populate Site Boundary Curve: Randomly distribute the amount of desired nodes as points within the boundary curve. Use the random seed to explore different point distributions.

2. Triangulate Population Points: Implement Delaunay mesh triangulation to generate a mesh that sits within the boundary. Naked mesh vertices are projected back onto the boundary curve, causing the pavilion to always terminate at the perimeter of the site.

3. Calculate Minimum Spanning Tree: Extract the edges of the mesh and convert to a graph using the NetworkX Python library. Calculate and extract a minimum spanning tree from this graph. A tree is a graph in which any two vertices are connected by exactly one path. A minimum spanning tree is a sub-graph that is a tree connecting all the vertices together. In other words, all the nodes in the graph will be connected using the minimum number of edges, yielding no cycles and low node valences.

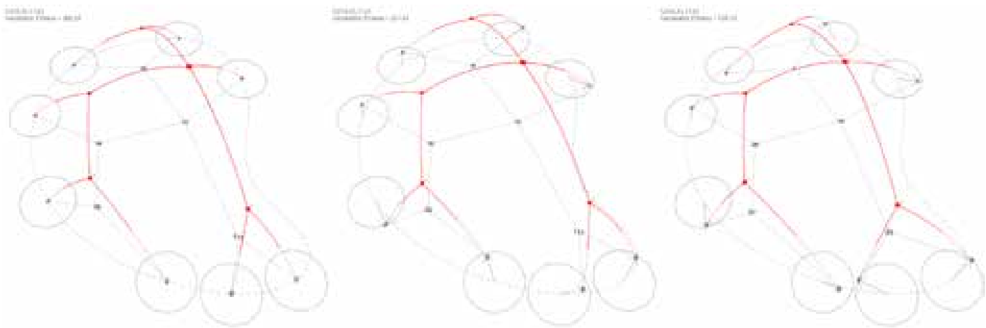


Figure 8:
Three states of single-objective optimization of the network angular fitness. The circles indicate the range of allowed movement for the support positions. The node values in black denote the local angular deviance from the ideal. G = [NodeCount, RandomSeed, GravityMagnitude, MaxShellCount].

Figure 9:
Three states of multi-objective optimization of the network angular fitness and total displacement. The coloured mesh indicates the local displacement values from the FEA analysis. G = [NodeCount, RandomSeed, GravityMagnitude, MaxShellCount].

4. Relax Network: Implement Kangaroo to minimize the edge lengths of the minimum spanning tree graph, thereby redistributing nodes with a valence higher than one, yielding more uniform arch lengths. This is a local feedback process.

The form-finding process for the catenary arches network was implemented using a model similar to that described in the Introduction of this paper. In the interest of time and to separate modelling concerns, we primarily focused on the form-finding of the catenary arches. The form-finding of the infill shells was implemented as its own separate process downstream. A primary development challenge here was enabling the geometry of the infill shells to "piggyback" along with the form-finding of the arch network. This was resolved by generating a mesh describing the infill shells in their initial state and passing it along with the arch network geometry. The modelling algorithm was encapsulated in the FormFindCatenaryNetwork component. The input is a graph network consisting of lines, values for spring stiffness and gravity magnitude, the site hull and the shell mesh. The modelling algorithm is divided into a pipeline of three processes:

1. Discretize Network Edges: Subdivide the edges of the network N times and generate polylines representing the catenary arches in network prior to form finding.

2. Make Solver Constraints: Generate the Kangaroo forces needed for form-finding. Each edge of each polyline is a spring, while each control point of each polyline is a particle subjected to a unary inverse gravity force. Each node with valance one is used to anchor the network.

3. Run Form-Finding Process: Solve the constraints using Kangaroo's zombie mode. This enables us to automatically stop the solver once the kinetic energy of the systems drops below a defined threshold. This is a local feedback process.

There were many meaningful design criteria to optimize for, such as area zoning, views and environmental factors. However, the structural design criteria required by the aim of the summer school to construct a 1:1 pavilion were given high priority. These concerns were addressed in the developed modelling pipeline by focusing on two primary objectives: optimizing geometrical properties desirable for fabrication, and minimizing the displacement of the arches network. This required the development of several models, implemented in the outer scope of the modelling pipeline:

1. Analyse Geometric Fitness: The analysis of desirable geometric fabrication characteristics focused on ensuring that the angles at which arches meet in a node are uniform. For example, for a node with three neighbours, the ideal internal angles are defined as 360/3 = 90. All internal angles are measured and the total deviance for each node is returned and used as a fitness value, which should be minimised. This again uses a graph as the representation and Python for the implementation. This was encapsulated in the NodeAnglesFitness component.

2. Analyse Structural Fitness: Analysis of the structural fitness was defined as a problem of minimising the total displacement of the catenary arches. This value was calculated

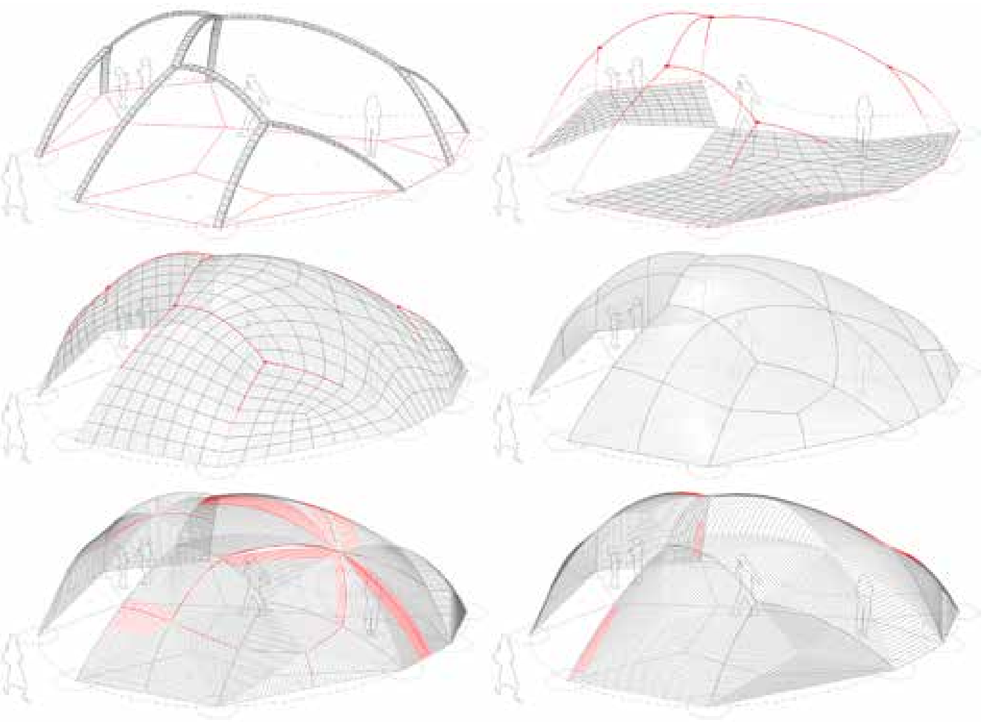


Figure 10:
From top left: The first two images show the process of generating the shell mesh. The third image is the mesh after form-finding and the fourth is the resulting network of NURBS patches. Images five and six are generated bonding patterns using two different diagonal settings. Red geodesics are not planar.

using the Finite Element Analysis plug-in Karamba using a two-stage pipeline. First, the form-found arch polylines are subdivided so that each segment corresponds to the dimensions of a brick. These segments are converted to beam-models with a cross section of the other two brick dimensions. Supports and loads are then added to the assembly, and finally the model simulation is calculated. This is encapsulated in the StructuralFitness component.

3. Update Support Point Variables: The phase space defined by MakeSiteGraph is not a good candidate for the implementation of generic solvers due to its discontinuous fitness landscape (as it uses randomness). Therefore, we focused on optimizing a fixed network topology once a manual search has resulted in a desirable design instance. The phase space for this search is defined by the magnitude of the gravity constraint used in the form-finding process and the XYZ coordinates of the support positions. The latter is defined as a list of floats with the number of supports multiplied by three. This can be tedious to manually set up and adjust when the topology changes. To alleviate this inflexibility, the UpdateSiteGraph model was developed. It takes the output of MakeSiteGraph, finds all nodes with valence one, determines the XYZ values of these and sends these upstream to a dynamically adaptive genepool which sends the values back and updates the support positions on change. This is an example of adaptive bidirectional feedback.

4. Run Optimization: To run the automated design space search, two generic solvers were implemented. For single-objective optimization of the angular fitness, the standard Grasshopper plug-in Galapagos was implemented. For multiple-objective optimization of both angular and structural fitness, the plug-in Octopus was used. In both cases the fitness values is connected downstream to the generic solver components and back upstream to the gravity magnitude slider and the genepool used for moving the support positions. A GUI is used to run either solver. This is a global feedback process.

The design criteria for the infill shells were relatively under-defined in comparison to those of the catenary arch network. An intuitive geometric description for the shells was defined as the closed polygons that are constructed as a product of calculating the convex hull of the site graph and combing the two. The development challenge was then determining how to find these polygons, how to generate a geometry representing them that could piggyback along with the arch network form-finding model and how to use this geometric representation to generate a meaningful brick-bonding pattern for each shell. To solve this challenge, four models were developed and implemented in the outer scope of the modelling pipeline:

1. Generate Shell Polygons: To automate the generation of the infill shells, we again turned to methods from graph theory. By adding the edges of the hull to the site graph, we can analyse the graph for cycles and extract these as polygons. This yields closed polygons in between the arches that terminate at the site boundary.

2. Generate Shell Mesh: The piggyback mesh is constructed by finding the centre of each shell polygon and connecting its vertices and edge midpoints to this point, yielding a quad mesh that can be subdivided to match the level of subdivision of the arch polylines.

3. Form-Find Shell Mesh: Once the shell mesh is output from FormFindCatenaryNetwork, it is passed on to its own form-finding model. By anchoring the vertices that sit on the arches and the hull, a pleasing shell can be generated using a combination of catenary constraints and pressure force along the normals of the mesh. This is implemented using Kangaroo and is a local feedback process.

4. Generate Bonding Patterns: By mapping the shell mesh subdivision, it is possible to convert the initial quads to non-uniform rational Basis spline (NURBS) surfaces. The UV parametrization and methods exposed by these surfaces enable us to develop bonding patterns based on geodesics. These are shortest paths on a surface between two points that are close to planar, which is a desirable property for brick bonding patterns. This is implemented by selecting a diagonal from which to start and a number of subdivisions along the edges of the NURBS patch.

The primary objective of developing a flexible modelling pipeline enabling exploration of the topological diversity of catenary arch networks was successfully met. Special attention should be given to the fact that the developed Grasshopper definition constitutes one coherent modelling pipeline with multiple levels of complexity in the form of feedback loops and bidirectional dataflow; without it, the design modelling is unmanageable, slow or disruptive. The individual sub-models are lightweight, well encapsulated and logically decoupled from each other. As a design search tool with which a user may engage in a creative and meaningful dialogue with what Negroponte (1970) would call an architecture machine, the results are satisfying. The synthesis of the design space and performance space in the form of the FEA analysis implementation is questionable and likely overly simplistic. It does not take the shells into account nor the rotation of the bricks along their catenary curve. The shell modelling is underdeveloped but shows promise. The challenge of laying out brick bonding patterns on arbitrary geometries is indeed an interesting one, which might be further developed based on the ideas presented here.

While generic solvers for searching the design space were implemented for optimizing both single and multiple design criteria, they were in effect only exploring metric variations of fixed design instance topologies. Therefore, while the modelling pipeline successfully generates topological variation, the automated generic search does not explore qualitatively different design options; more fit design candidates may exist. This approach was not researched further because the MakeSiteGraph model implements processes that use randomly generated numbers to generate the arch networks. This causes the fitness landscape to become discontinuous and thus hard for a solver to meaningfully traverse to incrementally find better and better candidates. That said, a brief round of experimental searches did yield fit candidates with highly diverse and interesting topologies. This suggest that generic solvers, or even fully randomized search processes, might become meaningful design explorers if the modelling pipeline and its constituent models, their design logic and underlying algorithms can be synthesised into a meaningful whole.

Acknowledgements

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Digital Simulation for Design Computation in Architecture

David Stasiuk and Mette Ramsgaard Thomsen

Digital simulation is currently used for architectural design in a broad range of both design-led research and professional practices for a wide variety of functions. Among other applications, simulations of different types are capable of representing material behaviours in structural assemblies (Tamke, Stasiuk, and Thomsen 2013), of directing form-finding operations (Kilian and Ochsendorf 2005), and of illustrating the impact of geometric organisation and material assembly on environmental considerations in relation to lighting (Ward 1994), thermal performances (Larsen, Foged, and Jensen 2014) and fluid dynamics analyses (Bartak et al. 2002). It has been extended into predicting patterns of occupancy across multiple scales, from the individual inhabitant (Shen, Shen, and Sun 2012) to urban-scale circulation flows (Farenc et al. 1999). Some architects assert simulation-based techniques beyond efforts to describe "real" systems and deploy them through generative tools, where they are used to activate agent-based design systems or algorithmic constraints whose rules are formally-driven or highly abstracted (Nicholas, Stasiuk, and Schork 2014). Despite these advances – and of course with certain exceptions – the application of digital simulation in architectural design in crucial ways lacks the maturity of methodology and instrumental sophistication available to simulationists in the natural sciences and engineering. It should be noted that frequent references will be made in this paper to the "natural sciences and engineering." The breadth of these fields is recognised, as is the necessary compression made in any characteristic statement about them. Any reference made to these groups in relation to their deployment of simulation therefore focuses almost entirely on tendencies and is certain to contain both exceptions and omissions. Furthermore, the decision to locate engineering with the sciences rather than with design disciplines

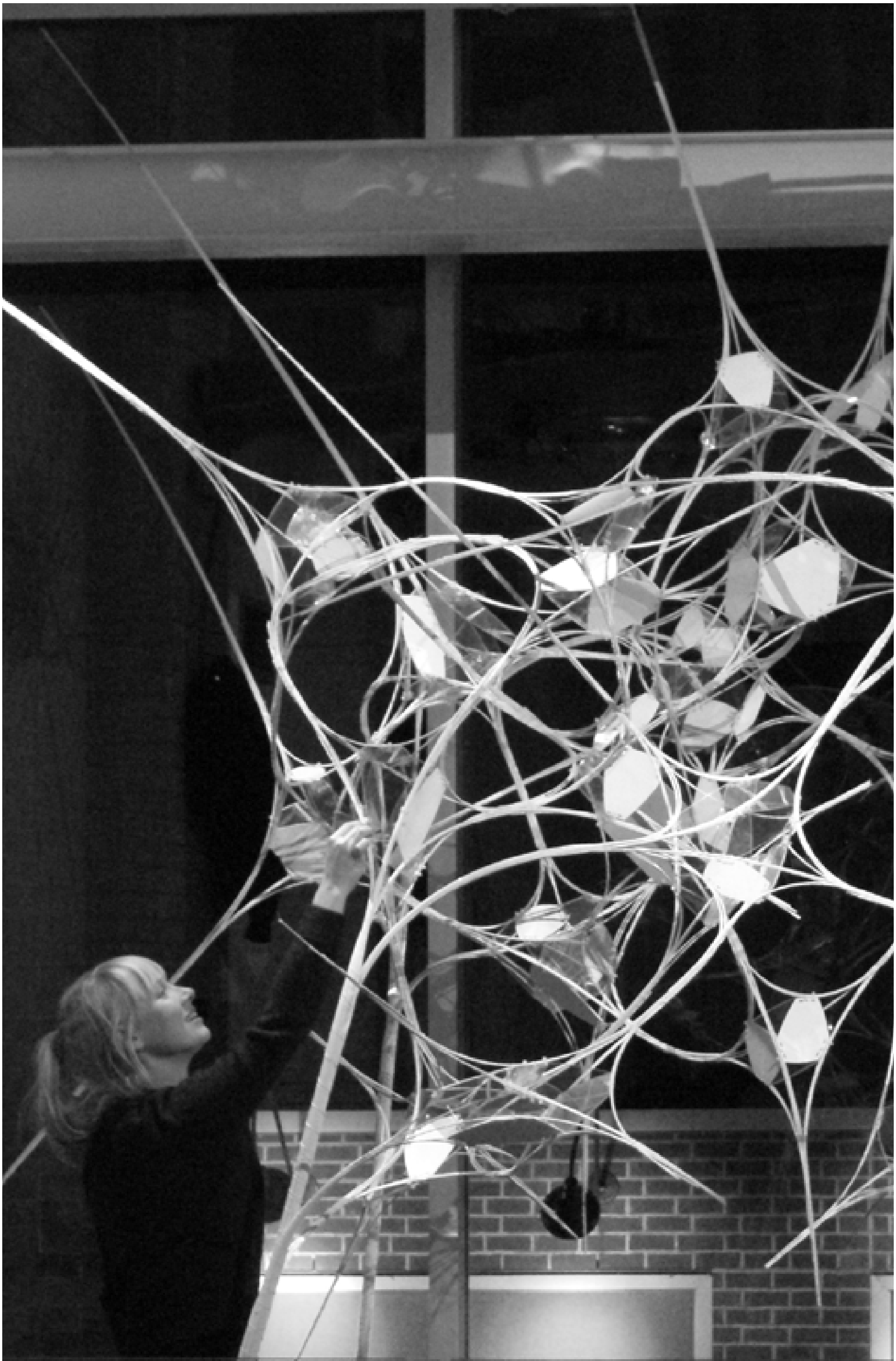


Figure 1:
The ACADIA Rise

is recognised as contentious. It is based here on a primary assertion that engineering is more generally an "applied science" that is concerned with well-defined problems that have clearly discernible boundaries for evaluation. This apparent disparity in the application of simulation in architectural design versus the harder sciences seems due to a number of important factors related not only to the history of simulation and computation, but also to key epistemological differences between design disciplines and the sciences. This paper reflects on those qualities in purpose, model construction, and evaluation that distinguish design simulation from scientific simulation.

Structure and background

This paper will be organised in four sections. After the introduction, the second section will briefly contextualise simulation as a design concern relative to the field of architecture's own traditions of representation as well as to simulation as it pertains to the natural sciences and engineering. It will also outline the argumentation for understanding differentiated epistemologies for design simulation versus scientific simulation. The third section uses a series of three case studies that provide an exploratory framework on this topic through an interrogation of difference in each project's application of simulation techniques, with a specific focus on meterial behaviour, structural performance, and interactive form-finding. The final section of the paper will collate the findings from these experiments in a reflective discussion about simulation for design computation in architecture. The research for this paper is produced for the 2014 Utzon(X) Summer School, and is a component of David Stasiuk's PhD research within the "Complex Modelling" framework at the Centre for Information Technology and Architecture (CITA). This project is a Sapere Aude Advanced Grant research project supported by The Danish Council for Independent Research (DFF). The grant was awarded to Mette Ramsgaard Thomsen. The project started in September 2013 and will run to August 2017.

Simulation frameworks

Since the advent of the computer in the middle part of the 20th century, digital simulation has played an increasingly important – even essential – role in the study of the natural sciences and in engineering research and practice, fostering entirely new approaches for hypothesis development and testing, and enabling new experimental methodologies. In broad terms, scientists use digital simulation as a proxy for physical experimentation. Through it they test existing theories, investigate new frontiers, and make predictions regarding the behaviours of attendant or integral complex systems. Engineers use simulation not only to calibrate and optimise well-understood assemblies such that they can produce solutions they are confident will meet performance criteria, but also as experimental platforms to develop and to test new strategies for continuously extending their capacities to produce such measurements into new territories of knowledge.

Soon after the construction of the earliest digital computers in the 1940's, researchers and computer scientists sought to both develop digital frameworks and formalise general approaches for modelling and simulation that could be applicable over multiple topics of inquiry. By 1960, a specific field for modelling and simulation (or "M&S") had emerged, with its own rapidly evolving methodologies and epistemology (Nance and Sargent 2002). This rapid specialisation by a subset of computer scientists toward the development of modelling approaches idealised for their application over any type of system belies the fact that the very earliest digital computers – such as the British Colossus and the American ENIAC – were often developed with specific calculations to

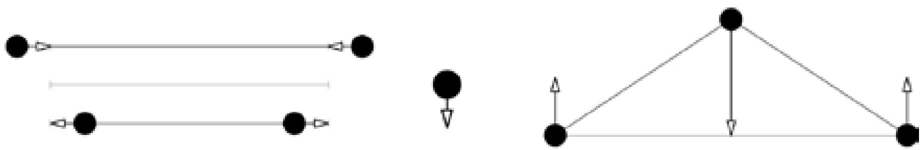


Figure 2:
Base forces applied for the particle-spring simulation for The ACADIA Rise.
From left to right: 1. Spring, 2. Unary and 3. Bending.

be performed in mind. The visionaries who designed them came from a variety of fields, and were exploring computation in order to create tools for themselves such that they could model, investigate, and systematically calculate on unprecedented scales highly domain specific functions. Of course, people like Alan Turing had an intense interest in and were highly motivated by more generalised computational theory. For example, Turing's own famous work on the"Entscheidungsproblem" is one of many that delves deeply into computational abstraction and is motivated by the more purely mathematical (Turing 1937). And indeed his and his contemporary's work was built upon foundations set by even earlier visionaries, such as Charles Babbage, Ada Lovelace, George Boole and John Venn (Bullock 2008). But Turing also was deeply interested in computational development for specific and applied purposes, famously for code breaking during World War II and later in the deployment of algorithms that could describe complex and emergent behaviours seen in chemical reactions and natural patterning (Lepp 2004). John Von Neumann's contributions to computational development were at least as vigorous and vital, and even more directly tied to the pursuit of applied research in a massive diversity of fields, especially military interests and nuclear physics (Eckhardt 1987). These earliest developments in digital instrumentation during the middle part of the 20th century were the product of an ongoing objective for digital computation to provide mechanisms suitable for modelling, describing and predicting the behaviours of target systems. Fundamentally, the early visionaries were developing these engines to perform simulations, and the communities that emerged around computation in these early years reflect this polyglot approach. It was then only after simulation was deployed in direct application that it formally emerged as a topic of interest in itself. Its history in science and engineering is then front-loaded with practice-oriented interests first and foremost, its contemporary formulation into a neutral framework pursuant to its functional use.

As is natural in the evolution of any field of study and its epistemology, since the advent of M&S as an independent field the term "simulation" has accumulated a variety of occasionally contradictory definitions. For this paper, simulation will be defined as "the process of developing a simplified model of a complex system and using the model to analyze and predict the behavior of the original system." (Ören 2011) In practice, simulations rely on the process of describing sequences of changing states for the target system under inquiry. They iteratively use the information encoded consecutive states to develop their predictive calculations for the next. For the scope of the discussion here, the interest lies specifically in continuous simulation models that produce actionable information through iterative computation.

Prior to the formalisation of M&S practices starting in the 1950's, functionally-driven, simulation-based practices had already taken purchase through analogue media in a variety of fields. Interestingly, architectural design has a rich and well-documented history in this vein. In the field of architectural design, then, the types of continuous simulation practices pertinent to the argumentation of this paper exist along two trajectories. These can be differentiated both historically and according to relevant media, with the first comprised of analogue simulation approaches for architectural form-finding, and the second reflecting the translation of these practices into a digital environment.

Early analogue simulation practices in design are directly related to the dynamic

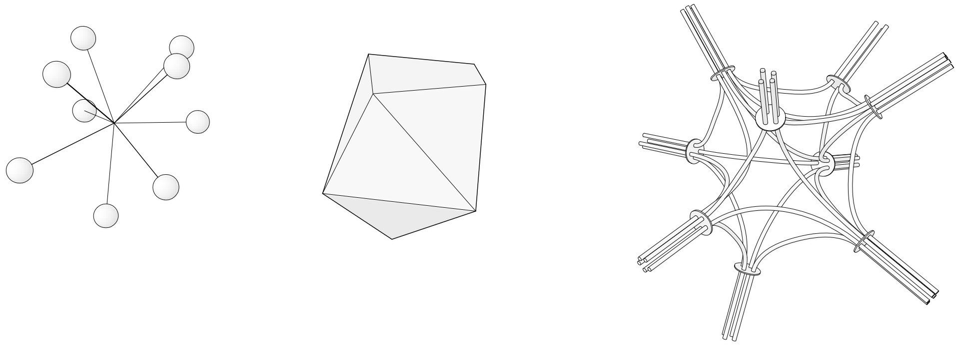


Figure 3:
Digital prototype illustrating use of convex hull topology to develop connectivity and structural organisation of nodes.

form-finding of structural systems, largely by master-builder architects or engineers. Their origin can be located in Robert Hooke's work demonstrating the structural performances associated with the catenary arch in the latter half of the 17th century, and their maturation traced through the 19th century with the formalisation and mastery of graphic statics (Allen and Zalewski 1996). For many of the early practitioners of these techniques, these tools were used to calculate or reflect upon designs that had already been asserted from the top down. But starting with Antoni Gaudi in the very last part of the 19th and early parts of the 20th century, these methods were extended in the creation of dynamic form-finding "designing machines" (Huerta 2006). Gaudi is of course famous for his hanging chain models that extended 2D representations of catenary networks into complex 3D vaults, as in his work for the church of the Colonia Guell. But he also worked extensively using graphic statics approaches specifically as a generative drawing tool for form-making, as did such other engineering visionaries as Robert Maillart and, later in the 20th century, Pier Luigi Nervi. Heinz Isler also worked through analogue simulations of shells through hanging textiles. The primary contributions made by these and others is tied to the types of form-finding they were able to derive from analogue drawing and modelling practices, especially in regards to the discretisation and simplification of complex material and structural performances into tractable, design-oriented systems.

For these practitioners, despite the maturity of their approaches toward analogue computation, there was little explicit notion that they were performing "simulations" as defined here. Of course, a great deal of their work preceded serious developments in applied digital M&S. And indeed, even following the advent of digital computation, the sophistication specifically related to form-making available through analogue techniques vastly outstripped any capacities afforded by newer digital simulation tools which – attended by a series of important developments in finite element modelling, especially in the 1950's and 1960's (Thome´e 2001)– first emerged as evaluative rather than generative instruments. This apparent discrepancy between computational applicability toward form-making between the analogue and the digital is exemplified in the practice of Frei Otto at the ITKE. In important ways, his body of work represents both the apotheosis of analogue simulation and its hinge toward a digital practice, as his practice increasingly relied upon the analytical capacities afforded by digital computation even as they continued to push the computational power of material assemblies through rich and disciplined form-finding investigations.

The maturation of M&S has run lock-step with advancements in electrical engineering and computer science practices – over the second half of the 20th century and now well into the 21st – and is marked by an attendant expansion of knowledge in multiple directions. It has grown broader in the sense that fundamental tools have become more powerful in terms of computational capacity and flexibility of application, and approaches have become codified for general application independent of topic. And it has grown deeper in the sense that highly focused, domain-specific applications are developed for modelling complex, individualistic systems within discrete fields of research and practice (Nance and Sargent 2002). Finally, these technical and methodological developments have been tracked through an emerging epistemology of simulation, especially as it pertains to practice in the sciences, engineering, and design disciplines (Winsberg 1999).

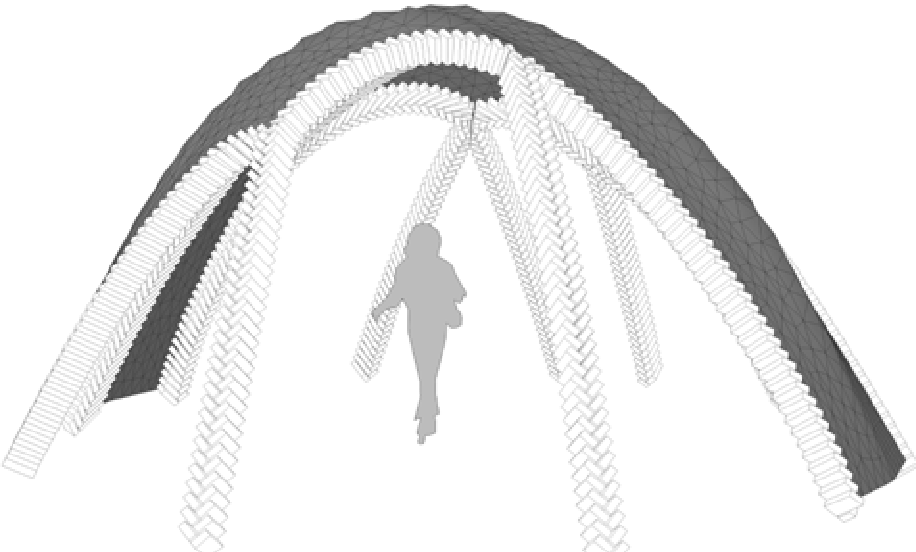


Figure 4:
Ribs specified at the resolution of the brick (yellow) and vaults generalised as a coarse mesh (grey).

Two key operations in building and testing a simulation model are validation and verification. In "Science in the age of computer simulation," Eric Winsberg focuses on these operations not only for their functional purpose but also as the key concepts in an epistemology of simulation. In simplest and most ideal terms, validation refers to a model's internal consistency in construction and correctness in executing its constituent methods of calculation, and verification refers to a simulation's capacity to correctly describe or predict the behaviour of the system it is modelling. However:

> *The epistemology of simulation does not divide as cleanly into verification and validation as this picture suggests. I would argue, that is, that simulationists are rarely in the position of being able to establish that their results bear some mathematical relationship to an antecedently chosen and theoretically defensible model. And they are also rarely in a position to give grounds that are independent of the results of their 'solving' methods for the models they eventually end up using.*

Here Winsberg points out that, ideal practices aside, developing simulations can be a messy enterprise. In fact, he spends a considerable portion of time outlining how simulation construction is akin to sausage-making: it is often a mash-up of multiple theoretical bases that require complex handshaking algorithms and are accompanied by stabilising "fictions" that lie outside the purview of theory and simply act as numerical instruments for maintaining order in a model. Yet regardless of the ambiguity this functional heterogeneity introduces to simulation modelling, processes of validation and verification must ultimately sanction only those models whose direct fidelity to the systems they aspire to describe are observable in practice.

With all of this in mind, Winsberg ultimately asserts that simulations are situated somewhere outside of both theory and experimentation, and represent a new and critical mode for developing an understanding of target systems, and for predicting their behaviours in projective environments. But his interest is also primarily in the sciences and those aspects of engineering where knowledge production, system and theory testing, and predictive analysis are the dominant goals for practice. How these ideas fold into an epistemology for simulation in the design disciplines – and here specifically architectural design – opens up new avenues for discussion (Winsberg 2010). In "The Sciences of the Artificial," Herbert Simon distinguishes design as "artificial science" in contrast to the "natural sciences:"

> *The natural sciences are concerned with how things are. Ordinary systems of logic the standard propositional and predicate calculi, say serve these sciences well. Since the concern of standard logic is with declarative statements, it is well suited for assertions about the world and for inferences from those assertions. Design, on the other hand, is concerned with how things ought to be, with devising artifacts to attain goals.*

Simon continues to describe that the sciences are necessarily driven through a process of deductive reasoning, and that while design processes that are clearly defined and open to optimisation are also open to these types of logics, at least as often design is concerned with problems that may not be fully optimised. And indeed, architectural design relies on parameters that are well-documented as being inherently broad in

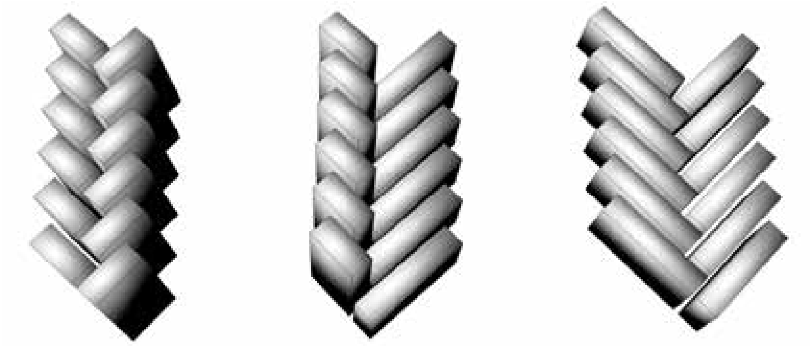


Figure 5:
Variable herringbone configurations for precisely specified rib bricks: free-standing column (left) column open on one side and supporting a vault on the other (middle) and supporting vaults on both sides (right).

scope, varied in type, and often self-contradictory in nature. Architecture is therefore particularly prone to the "wicked problems" endemic to design disciplines that "elude reduction" (Buchanan 1992). This complexity is of a fundamentally different nature than the types of complexity simulationists seek to unravel through the modelling of systems in the natural sciences and engineering, which in many cases are more directly measurable. Simon would suggest that it allows for a move from deductive to inductive reasoning to find solutions that are good, if not optimised, an affordance he terms "satisficing" (Simon 1996)).

Certain observers suggest that the emergence of simulation in architectural design is in fact simply attendant to the deployment and adoption of computerised tools – first through CAD, and then BIM – and as such by the end of the 20th century were already deeply embedded in most architectural practices (Loukissas 2008; Turkle et al. 2009). Shelly Turkle, for example, sees a designer spinning a 3D CAD model on a computer screen or producing a rendering of a digital model as working through simulation. This inclusive characterisation of representational practices as modes of simulation makes sense in the context of her larger argument about the sea-changes in both the design and scientific communities that have come through the often chaotic transition from primarily analogue to primarily digitally-based practices. But in key ways it contrasts with the argument made here, which takes the position that simulations operate in ways that are fundamentally different from pure visual and even spatial representations, regardless of their resolution or enhanced sensual tactility. The argument runs somewhat parallel to the idea that "computerised" design practice does not necessarily embody a "computational" design approach. In such a distinction, computational approaches enact key transformations to input parameters in the creation of new information about the design system, while computerised approaches need only operate in a digital platform, translating instructions without necessarily providing additive feedback. Even a complex 3D model can be "hand-drawn" – or computerised – in a CAD system: perhaps visually dynamic, but inert as an intrinsic generator of new information. As such, it operates as a receptacle for a design decision that has already been made.

As discussed, analogue simulation techniques for form-finding in architectural and structural design significantly pre-date the advent of the digital computer. Yet in contrast to modes of simulation for the natural sciences and engineering that paralleled the advancement of computer science from its origins through today, the development and adoption of similar form-finding architectural modelling techniques through digital instrumentation have only relatively recently emerged, firmly established by Axel Kilian and John Ochsendorf's 2005 paper "Particle-spring systems for structural form finding." This paper presents a methodology specifically oriented toward the digital production of a funicular modelling environment that digitises the analogue hanging chain material computational strategy Gaudi employed for those complex vaults developed through catenary networks. Borrowing from developments and digital tooling well established in computer graphics and animation, the authors detail a methodological breakthrough that frames simulation specifically for form-finding these idealised structures (Kilian and Ochsendorf 2005).

Critical to the relevance of these techniques are two dependencies. First is the affordance they provide for architectural designers to rapidly develop open-ended digital design tools to experiment with form-finding observations that are endowed with plausible representations of material behaviours and structural performances.

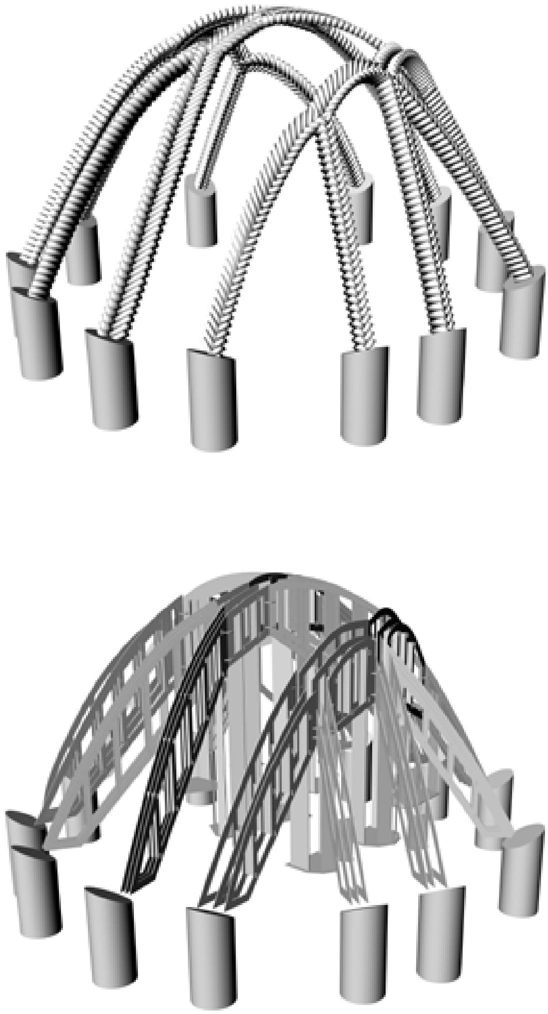


Figure 6:
Rib networks (left) and the scaffolding system for precision location and orientation (right).

Secondly, they enable a parametrically controlled sculptural flexibility which empowers designers to assert authorship – often in ways contradictory to what a materially “optimised” approach would produce – in pursuit of those aspects of invention and discovery that produce inductive and integrated responses to “wicked” design problems. The particlespring systems introduced by Kilian and Ochsendorf as architectural design instruments exemplify such an approach. And model validation in this context is derived from understanding the simulation schema for their basic connection to the underlying mathematics of Newtonian physics, to their historical precedence in computer science and engineering, and further as rooted in the earlier analogue simulations described above. But as such approaches become increasingly adopted, they have been extended through a number of alternate proposals and projects that introduce and examine less easily validated modelling setups. Physics simulations are frequently integrated with multi-agent systems that rely on designed forces to assert further authorship over design environments, optimisation instruments that press form into arrangements more suitable for fabrication, and other modes of performance evaluation. The validations of such hybrid models becomes perhaps more ambiguous and less deductive. And the question of their verification remains even more open. How are such models evaluated? How can design simulation that is guided by induction be sanctioned?

Case studies for design simulation modelling

This section begins to frame these questions through design-led research, focusing on simulation strategies deployed for three different projects. The first is The ACADIA Rise, an installation realised through a design/build workshop led by CITA during the 2013 ACADIA conference at the Waterloo School of Architecture in Cambridge, Ontario. The second project refers to the design model for the Utzon(X) Masonry Pavilion, which is developed during the 2014 Utzon(X) Summer School program held at the Department of Architecture and Media Technology, Aalborg University. The third project discussed is the Stressed Skins installation developed by CITA for exhibition at the Danish Design Museum in Copenhagen in the Spring of 2015.

Each of these case studies focuses on its own distinctive computational modelling approach in the application of digital simulation techniques for an integrated design system. For discussion, both similarities and differences are highlighted in order to provide a framework for understanding how strategies in model construction for design simulation can be tailored and evaluated in the synthesis of variable ranges of design goals. In these particular examples, these ranges are comprised of varying mixtures of material intelligence, constructibility, structural performance, and design authorship. The design goals and basic modelling schema for each project will be outlined individually. This will set the base for a later discussion reflecting on approaches for validation and verification.

The ACADIA Rise

The ACADIA Rise is an architectural installation that extends CITA’s research into bending-active structural systems. Here, fibrous and flexible glass-fibre reinforced polyer (GFRP) bundles multiply, bend, branch and recombine at nodes of hard acrylic convex polyhedra that hybridise the assembly into an organically distributed, spaceframe-like spatial structure.

The computational interest for the experiment lies in the production of loosely bio-mimetic, dynamically activated generative models. Their aim is to implement form-finding processes based on recursive algorithms imbued with responsive feedback loops, such that the characteristics of constituent materials are continuously expressed

Figure 7:
CITA's Stressed Skins installation exhibited at the Danish Design Museum in Copenhagen.

through a simulation of their structural behaviours, occurring as each element is generated during model execution.

The bio-mimetic component of the algorithm is a direct extension of the modelling strategy deployed for CITA's earlier experimental structure The Rise. For both of these projects, "tropisms" that describe the mechanics of plant growth operate as a type of pseudo-code for the recursive growth process (Tamke, Stasiuk, and Thomsen 2013). In The ACADIA Rise, a set of four initial seed points are located in the target design space. They then sense their environment and extend GFRP shoots toward a virtual light source also located in the design space. As these seeds grow, they also sense proximity to each other. Within a specified tolerance, branches fuse together into triangulated, connective nodes. The formation of each node results in additional outgoing growth shoots, and the total assembly becomes increasingly dense over time. The growth algorithm is dynamically activated through a custom-coded particle-spring simulation system. Through this mechanism, the emerging form is modelled with direct dependence on the material assembly's physical behaviour under self-loading. Critically, the model is also configured to adaptively re-specify the bundle sizes of the GFRP rods and reparameterise the simulation accordingly.

This simulation system relies on a simple continuous Verlet integration of standard "forces" derived from Newtonian physics. It uses three of these common to such models: 1. a spring force that applies Hooke's Law to pairs of particles throughout the simulation, 2. a unary force that acts upon each of the particles to simulate the force of gravity, and 3. a vector-normal bending force that endows sets of three particles with elastic properties, which when laminated consecutively from subdivison points in a spline simulates the behaviours of bending-active members. This last force as implemented here was derived by Barnes, Williams and Adriaenssens (Adriaenssens and Barnes 2001), and later more simply represented by Moritz Fleischmann and Daniel Piker (who consulted in the coding of the custom simulation library developed here).

The hybrid nature of the structural assembly produces the most significant modelling challenge in the desire for an integrated representation of both the actively-bent elements between and the rigid elements within each node. The digital modelling of the nodes relies on convex hulls created around a spherical intersection with the bending active splines that meet at a given point. These hulls manage the connectivity between elements in terms of their topological relationship, and simultaneously produce the geometry for triangulated spring forces that stiffen the connection node in the simulation. So the simulation model becomes a hybrid as well: with one set of springs and bending forces describing the struts between nodes, and another set of springs that represent the behaviour of the rigid plates that both define connection topology and stiffen the nodes.

The Utzon(x) Masonry Pavilion

For the Utzon(X) Masonry Pavilion, the ambitions of the design brief are explicit from the outset of the design process. The goal is to produce a funicular vaulted masonry construction within a set building site. This construction must integrate a consideration of its architectural expression with the activation of variable thermal properties from differently coloured bricks, which in this book is described in greater detail in Isak Worre Foged's chapter "Finding Thermal Forms."

In order to make these multiple goals tractable, the modelling process is discretised into multiple stages. The segments discussed here are tied to the model that executes

Figure 8:
Interior view between upper and lower skins showing formed connections and patterning.

the simulation-based funicular form-finding for the overall configuration of the pavilion intended to help direct masonry work in realising the complex generated rib and vault geometries.

The funicular simulation is developed using Kangaroo, a particle-spring physics simulation plug-in for Rhino+GH. The form-finding process relies on a combination of spline-networks for the ribbing, and area-independently loaded triangulated meshes for the vaulting. This allows for the ribs to not simply work as a network of hanging chains assuming individually planar configurations, but also integrates a simulation of the loading that results from the interstitial vaulting, pulling the ribs out of plane as they adapt to manage the self-weight of this more complex configuration.

The construction strategy targeted for deployment in the final assembly is comprised first of precisely located and strategically oriented masonry ribs that carry loads down to multiple discrete concrete foundations, and secondly of the infill vaulting that spans between these ribs. The detailing strategy for the ribs is based on herringbone pattern configurations that are varied according to each rib section's performative role.

The geometry of the vaulting is only loosely specified by the design model and, and is precisely located on-site under the direction of the master mason. As a result of this combination of pre-fabrication precision for the ribs and later in-situ resolution for the vaulting, the model evolves to represent varying degrees of specificity in the design geometry. On the one hand, highly detailed fabrication drivers are produced for the scaffolding used to guide the masons' work along the ribs during construction, which is resolved down to the level of individual bricks. On the other, the vaulting is indicated in the design model as a low resolution series of non-discretised triangulated meshes distributed between the ribs.

Each of these structural elements – the rib and the vault – is treated differently in the simulation, and the inverted weights of each in the catenary simulation are separately controlled by the designer, in order to 1. sculpt the final spatial condition toward the design brief, 2. create a rib geometry for which a scaffold is reasonable to build, and 3. provide the masons with a general vault geometry that is manageable according to the techniques that they employ.

Stressed Skins

The architectural installation Stressed Skins is free-form, frameless stressed-skin structure comprised of two layers of 0.5mm thick steel plates. The connection details between plates on each side provide the structure with depth for managing shear forces within the structure. All of these geometric elements, along with support for connections between plates on the same layer and tectonic patterning are robotically asserted through a process called single point incremental forming (SPIF).

The computational interest for the experiment lies in the dynamic activation of a multi-resolution unstructured mesh that adapts across multiple scales of design inquiry. It works as the underlying data structure for a variety of interdependent form finding operations, structurally and materially-driven simulations, and direct fabrication drivers for CNC operation.

Form finding The initial form-finding process relies on a generative growth algorithm that distributes two regular pentagonal tiling tessellations onto two free-form doubly-curved target design surfaces. The tiles themselves are instantiated using two .NET libraries that are directly integrated with the Rhino+GH modelling environment. The geometric and topological basis for the model is managed using the first of these, a half-

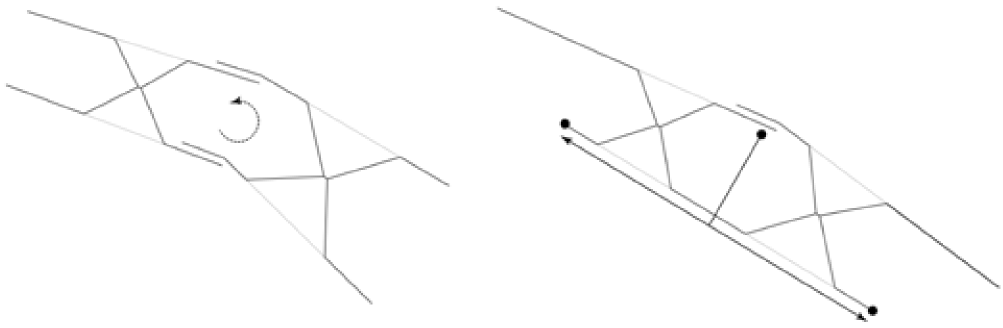


Figure 9:
Undesirable hinging condition (left) where seams align along both skins, and vertex repelling goal to minimise these instances (right).

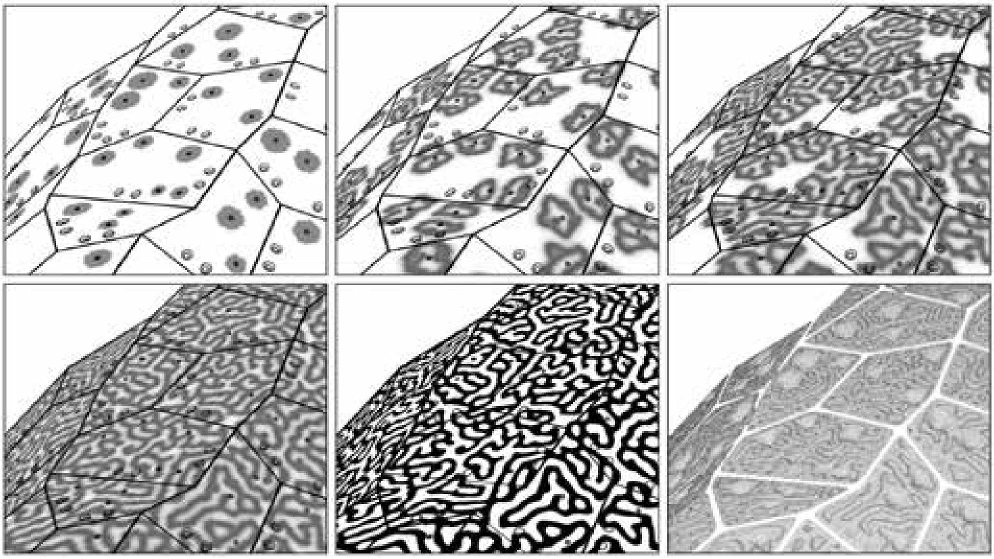
edge mesh data structure called Plankton. The form-finding simulation is then executed through a beta-version of the constraint (or "goal-oriented") physics-based Kangaroo2 library (Piker 2015). Through a direct scripting interface, Kangaroo2 enables the writing of custom goals over dynamic and transforming topologies. Because the tiling scheme used is developed for a planar condition, here individual tiles must be distorted in order to follow the geometry of the target surfaces. In the form-finding simulation, a collection of goals are used to resolve competing geometric assertions.

The base goals are related to edge-length maintenance and internal bending angle for each pentagon. Next, goals that draw each vertex to the appropriate target surface and repel it from the opposite (either for the upper or lower skin) are established, as well as a goal for polygonal vertices on opposite skins to repel each other, aiming to increase heterogeneity in panel connections between the two skins and minimise potential "hinging" instances. Finally, the introduction of a planarising goal is necessary to ensure each panel is suitable for fabrication.

Following the initial form-finding operations, a series of structural finite element simulations are executed, using the Karamba component group for Rhino+GH. First, shared territories where formable areas able to accommodate connections on both skins are identified, and "probe" connections are located within each of these territories. Then these probe connections are used to execute a finite element analysis, the results of which drive a further transformation, where connections multiply and reorient themselves in response to shear forces read. A second finite element analysis is then performed on this organisation, the results of which drive are used to create the two distinct tectonic patterning systems, one for the lower skin and one for the upper skin. The lower skin pattern is simpler, and comprised of a series of dimples located in response to high utilisations within each panel, and then secondarily oriented according to shear forces read from adjacent inter-skin connections. The upper skin pattern is more complex. First, its base form is globally derived through a Gray-Scott reaction diffusion simulation (McGough and Riley 2004).

Each panel is then discretised, and in a third series of finite element analyses subjected to translational and rotational forces derived from the second finite element analysis described above. Here, high levels of utilisation are identified, and used to locally activate an incremental introduction of depth to the reaction diffusion pattern. This in turn is used to recalibrate the local material properties within each panel, such that increases in stiffness related to increased geometric depth and hardness related to plastic deformation resulting from the forming process can be registered. Then these data are used to update the model, which is re-iterated through the same force application and responsive introduction of depth. This loop is run up to 15 times for each panel, locally introducing material transformations in response to the simulation of their local structural responsibility within the global assembly. The result is both an overall reduction in utilisation due to strain hardening combined with an increase in the total bending energy potential for each panel.

Each of the experimental models described above relies on simulation as a key formfinding instrument, through which it represents dynamic material behaviour in its generative algorithm. Although all of them use variations of a particle-spring system for the primary form-finding operations, each has its own particular setup, and crucially is developed with different design ambitions for output. The ACADIA Rise is focused



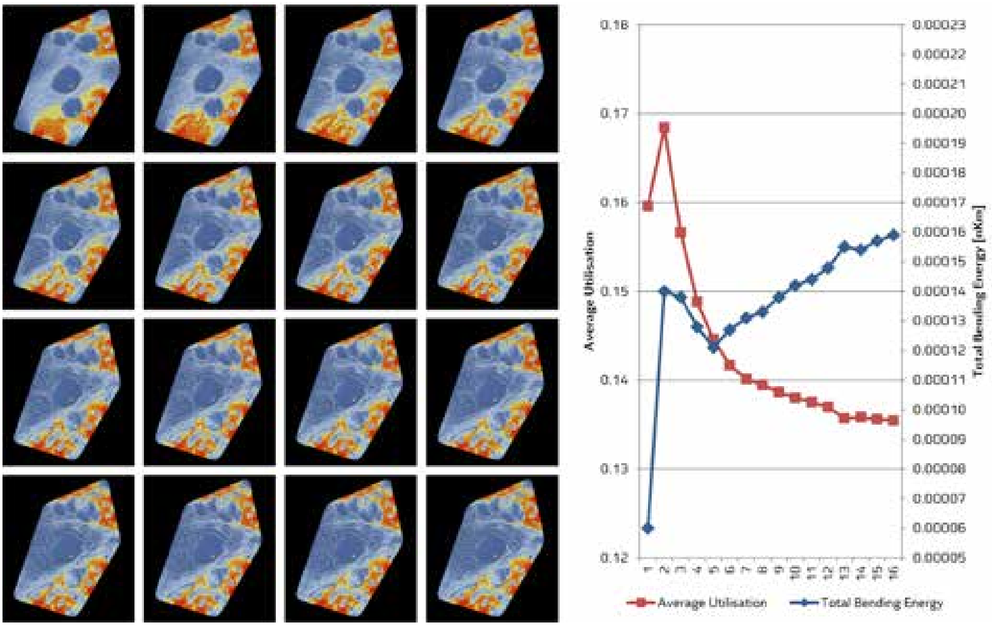


Figure 10:
Reaction diffusion simulation run on global mesh to array upper skin patterning, then integrated with inter-skin connections and discretised for each unique panel.

Figure 11:
Finite element transformations over 15 iterations of locally introducing depth and updating material properties for each panel (left) with related decreases in total utilisation due to strain hardening and increases in bending energy due to added geometric depth (right).

almost exclusively on the dynamic representation of a bending-active hybrid material assembly. The Utzon(X) Masonry Pavilion seeks to work with the well-understood potentials and behaviours of catenary vaults, but in a way that allows for the designer to trade an ideal structural capacity for a more nuanced management of spatial intent and fabrication potentials. Stressed Skins iterates through multiple stages and types of simulation. First, it deploys its goal-oriented particle-based simulation model almost exclusively through artificial forces that execute the generative form-finding algorithm and refine geometry for the purposes of fabrication. Then it uses finite element approaches to analyse structural behaviours and materials properties in its location and specification of connection details and in its tectonic expression.

A strong theoretical basis for the calculative techniques used is critical for sanctioning simulation models in the natural sciences. Their purposes include testing or extending these existing theories, building deeper knowledge about complex phenomena around the systems they describe, and predicting specific outcomes for a set of conditions in their domain of interest. As a result, they must be verified – or here "calibrated" – through a few clear methods: either through experiments, analysis, or other previously validated simulation techniques (Winsberg 1999). In each instance, the purpose for such models is to either achieve a maximum fidelity in their representations. Simulation for form finding in architectural design may be judged on somewhat different criteria.

Prototypes: Physical prototypes have long played key role in the development of architectural design systems, and indeed have become even more essential as digital computation techniques enable a greater range of modelling flexibility:

> *The relation between model of design and prototype gains importance as our understanding and relating of material systems to their simulated abstract models improves and computation increasingly becomes embodied in physical constructs replacing complex mechanical assemblies with computational feedback and control* (Gengnagel et al. 2013).

This ties directly into the role they play in the calibration of design simulation models, and is particularly applicable for those that are exploring new territories, techniques, material performances, or structural assemblies. For such systems where a theoretical foundation or precedent simulation schema may only partly validate model setup, engaging in parallel prototyping practices to evaluate the simulation system as it is being developed becomes necessary. Here, vital information for feeding back into the digital model is collected regarding material transformation, assembly performance, fabrication applicability, and global structural behaviours.

Authorship: In the case studies discussed, the variation in technique and simulation model formulation are driven by more than a theoretical understanding of the systems they endeavour to represent. As mentioned above, each is driven by its own set of design ambitions. It is these ambitions that drive the adaptation of what particular simulations need to – or even should – represent. This is a direct result of the projective nature of design, and what separates the artificial sciences from the natural sciences. Sanctioning a simulation model for architectural design relies on its capacity to correctly describe a material or assembly system insofar as the author prioritises this in the context of other design ambitions that may lie outside of the simulation's purview. So this fidelity works as one weight in a balance of complex intentionalities – such as those appropriate for addressing the wicked problems that designers face – and has its own range of acceptable tolerances. As design simulationists purse the ongoing development of better techniques for embedding material intelligence and complex assembly logics into digital simulations, they will continue to collapse these tolerances, and more clearly assert their authorship even as they take advantage of open-ended explorations in form-finding.

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Finding Thermal Forms
A Method and Model for Thermally Defined Masonry Structures

Isak Worre Foged

Introduction

Humans sleep, eat, play, sit, walk, read, exercise and rest inside buildings. As a result, we as humans spend by far the predominant part of our lives in enveloped spaces that are constructed. Each of these activities requires a particular environment so that sleeping is made more comfortable, reading is made easier, and playing is made more enjoyable. In the case of an architectural structure that does not meet these environmental conditions, there is a tendency to apply machinery, often in the form of lighting, heating, ventilation and air conditioning systems (Moe 2010). These systems often become a form of attached décor, a kind of unwanted architectural ornamentation applied to the structural components of the building. By a technical-mechanical approach, it has been argued previously that the activity or spatial programme has decoupled the articulation of the architecture. Further, the external natural climatic environment has unlinked both the building and the humans inside. What follows is the additional negative by-product of constant energy expenditure to run and maintain the machinery that compensates for the lack of environmental architectural articulation.

The inquiry of this study is to develop an approach to constructing thermal environmental architectures for humans based on multi-material constructions. This approach is based on the intent to increase the spatial quality and perceived architecture from a tectonic and thermal environmental sensory perspective.

The background for previous solutions is based on the ability to understand and simulate both a thermal environment and a design method through progressive steps. A design advances by iteration, as is the nature of the design process (Lawson 2006), but beyond a few proposals, this study utilise the method of applying evolutionary algorithms, whose basis relies on a multitude of rapid iterative processes for progression. Previous

Figure 1:
Brickwork bond combining two similar bricks but with different colours into a thermally composite heterogeneous masonry structure. Photo by author.

work combining thermal simulation with evolutionary programming has been done by Ali Malkawi et al (Malkawi 2005; Malkawi et al. 2005) focusing on Computational Fluid Dynamic (CFD) models and how to optimise the opening of windows and doors in a simple rectangular space. In their studies, they pair a commercial CFD solver with a standard genetic algorithm (SGA) based on an open, accessible programming library. Luisa Caldas et al (Caldas, Norford, & Rocha, 2003; Caldas, 2006, 2008) have performed similar studies by modifying an existing building design towards improved energy scores. This is done by coupling the DOE2.1E energy simulation engine with different types of evolutionary algorithms. Recently, David Gerber et al (GERBER & LIN 2012; Gerber et al. 2013) have worked on more diverse geometric forms than the previous studies by Malkawi and Caldas to apply the approach to architectural design problems closer to practice, by coupling multi-objective evolutionary algorithms (SPEA) with an energy simulation engine. The aim of this study was to improve energy balances and financial scores. Previous research work in this field is very limited and the above references lie on the periphery of the objective of this work, as they focus on bottom-line energy efficiency scores, rather than on the construction of specific thermal environments that subsequently may improve energy balances. Studies by others, organising matter to achieve spatial thermal properties by evolutionary computation, have not, to the knowledge of the author, been carried out before.

It has been attempted in this study to construct an architectural probe on the basis of the above aspect and previous studies and conclusions. The design model is constructed of three interacting models: a thermal environmental simulation model, an evolutionary model and a parametric model. The core investigation aims to explore the capacities for a multi-matter brick envelope and the effects of the organisation defining the perceived sensations.

From this, the study presents the theory and methods of perceived thermal environments for humans and how these are applied into the specific evolutionarily based design methodology. Following the description of the computational methods used and developed, a preliminary study is performed as an elementary setup to illustrate the method as a design approach. Based on this provisional example, a pavilion structure has been developed to construct a larger envelope with different climatic environmental orientations to test the ability to construct differentiated environmental formations across the envelope.

Three computational models are combined into one experimental research model for evolution-based development of environmental-human constructions.

In relation to the environmental simulation model, a new thermal solver has been developed, written in the programming language C#, to enable a fast iterative assessment for conceptual architectural design processes. The solver is directly applicable to the 3D modelling software Rhinoceros and the parametric modelling plugin Grasshopper. It was chosen to develop the solver as an extension of the previous environmental simulation models, as advanced existing thermal simulation solvers, such as BSim, IES and DOE2.1E, require a well-elaborated design before a simulation can be initiated, contradicting the approach of progressive development by evolutionary processes. While early design phase solvers exist, such as the software DIVA, they have too low a resolution of data output, allowing the experimental observer to register only accumulated values, rather than, for example, specified daily and sub-hourly simulation data.

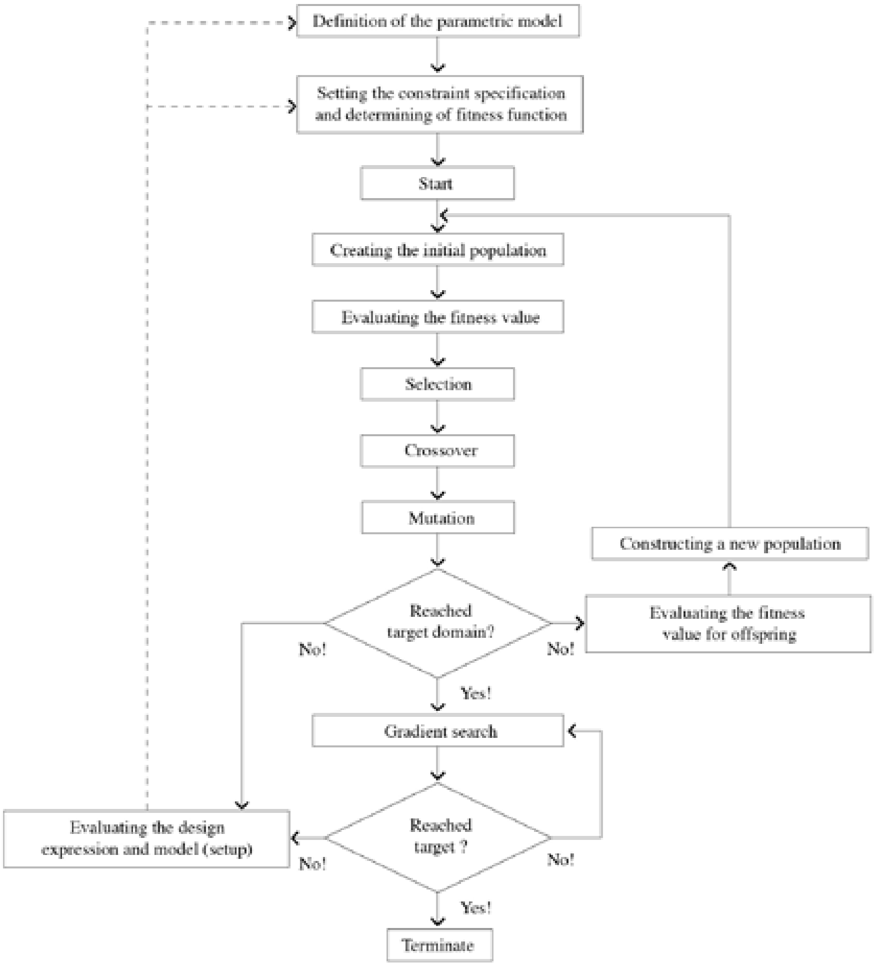

Figure 2:
Schematic diagram of an evolutionary design algorithmic process.
Diagram by author.

The thermal environmental solver integrates the equations provided by Fanger (Fanger 1970b; Fanger 1973) and some of their extended formulations. To further elaborate on the architectural potential of these perceived thermal assessment methods, one can initially consider the human aspects integrated, as the clothing rate says something about the condition a human is situated in. Many people will wear lighter clothing in warm summers and warmer clothes in cold winters. However, this is not always the case, as cultural-social influences may restrict this behavioural adaptation, with a bank being an example in which employees are seldom allowed to walk around in shorts and sandals. We see similar patterns with regard to the metabolic rate, which describes a person's physical activity and is also related to the local climatic environment; humans, for example, tend to sit more densely packed, keeping arms and legs closer to the body core in colder climates and according to the physical activities prescribed by the social situation. Being in a gym class at school simply does not allow a low metabolic rate, as it is determined by a situation in which physical activity is required. Less drastic everyday cases can be seen in the simple difference between the metabolic rate of an engineer at work of MET 1.2, while washing dishes has a metabolic rate of MET 2.5. Architecture may suggest a clothing style and a metabolic rate, but it would be difficult to dictate it.

When considering the environmental aspects, architecture is far more instrumental in the determination of the human thermal sensation. The ambient air temperature is naturally related to the external climatic temperatures unless the architecture is constructed as a thermally sealed container. By heating an architectural construct, for instance using the sun or the Earth, the internal air temperature can be modified by convective processes, in which the air is warmed or cooled and then reaches the human and adds to the perception of a thermal environment. More complex is the radiant temperature, that is, the temperature radiated from the surface of a space, including the direct radiation of the sun in glazed or open environments (La Gennusa et al. 2007; La Gennusa et al. 2005). Several considerations and assumptions must be included, such as whether a person is standing or sitting, body posture and where in the space the person is located, defining the angle factor in relation to the radiating surface. While complex to assess, the mean radiant temperature (temperature based on all the surfaces 'pointing' at a person) and the direct radiant temperature have a significant and interesting affect on humans' thermal sensations. As the sun moves across the sky, it will radiate and heat up surfaces that will either absorb the energy or re-radiate it back into the environment. This forms an interesting and challenging potential for architecture in that the designer can organise solid material to absorb and radiate energy, with the aim of influencing the mean radiant temperature and the resulting thermal conditions for humans. As a consequence, what is organised are states of matter. In this process, the capacity for air movement is determined by the porosity capacities of a given enveloped architecture. Lastly, relative humidity is largely defined by the external climatic environment while also being coupled to the ability to ventilate spaces and change the local humidity conditions by, for example, saturating air with water.

The work here focuses on the ability of architecture to modify the thermal sensation of humans in a specific environment through the articulation of radiant air temperature. This objective is approached by the organisation of thermal radiation through the distribution of a solid matter, brickwork, in different formations.

The mathematical models on which the simulation methods are based follow the current ISO standards (ISO 2005), but deviate in some aspects, as simplified methods have been

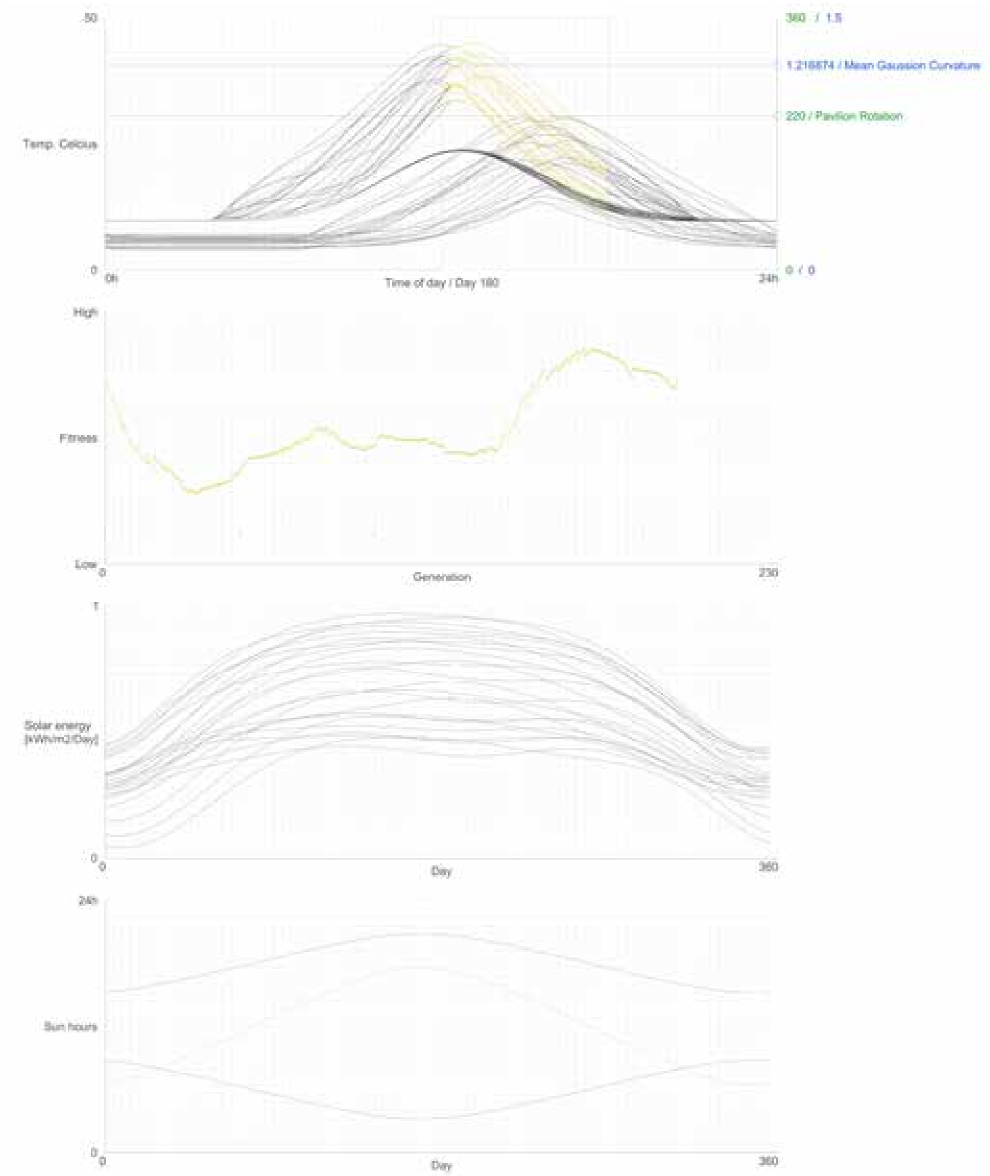

Figure 3:
Graphs plotting thermal aspects visible to the designer to understand and modify the design variables and evolutionary process mechanisms in order to explore the initial design and the possible space for design solutions and problems. Graphs by author.

used in part of the simulation to allow the simulation to be included in a design loop that requires rapid feedback. The developed models for thermal evaluation include (1) calculation of solar irradiance based on Lambert's Laws for solar geometry and physics (Oke 1987); (2) calculation of insolation on a given surface based on global irradiance, the sun vector and the normal vector of a given surface facing the sky, including detection of self-shade (ibid.); (3) calculation of temperature increase on the external and internal surfaces of an envelope based upon calculation of decrement factor and decrement decay (ISO 2007); and, finally, (4) calculation of perceived temperatures, comfort temperatures, operative temperatures, predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) based on the original Fanger comfort equations (Fanger 1970a; Fanger 1986; Fanger 1973) and the modifications to the mathematical models (Kerslake 1972; Höppe 2002; La Gennusa et al. 2005).

In design, it is argued (Akin & Lin 1995) that not only iterative but rapid iterative processes of sketching, analysing and synthesising increase the ability of the designer to create novel design decisions. As argued, the principle of evolutionary computational processes is the rapid iterative analysis of an element in relation to a defined environment. This adds to the previously stated arguments in favour of applying a progressive search methodology in architecture. Thus, evolutionary processes in this study are interesting, not only to optimise a pre-existing design oriented towards an optimum solution, as is the tendency in engineering processes (Rao 2009), but also to explore potential phenomena and computed proposals that lead to novel design decisions.

While they have been applied predominantly in the sciences, the processes of evolutionary simulation have also caught the attention of the philosophical field (DeLanda 2001; DeLanda 2011), as the processes capture the complexity of non-linear organisations present in other creative processes of design. Since the early explorations by John Frazer (Frazer 1995) in architecture, many architectural and specifically architectural engineering researchers have studied the behaviour, applicability and methodological potential of evolutionary processes.

Two search methods of finding thermal forms are applied in this study. The first is a method, entitled 'global search', that is searching stochastically (evolutionary search), meaning that it uses a form of random search, much like looking arbitrarily in all directions to find something of interest. This method covers the 'landscape' of possible solutions and simulates the initial design process in which solutions and problems are commonly defined vaguely. During the search, a series of potential solutions and problems can be detected, along with the design variables that are adjusted to get there. This narrows the search field, or design solution space, and the design variables can be more precisely formulated in relation to the design objective. A 'local search' (gradient search) method is then applied, which, instead of looking in all directions all over the design space, only looks nearby and in more fixed directions (Rao 2009). This two-step search approach allows for both a covering of a large quantity of design solutions and the possibility of finding incrementally better solutions for the intended aim of the design according to the fitness criterion, which in this case is a desired thermal sensation at a given time period. The evolutionary procedures in this study are applied through the open-source evolutionary solvers integrated into the Grasshopper framework developed by Rechenraum (Rechenraum 2013) utilising the open-access algorithmic library NLopt.

Figure 4:
Plan view of two pavilion simulation models. The model in the top includes a simulation resolution of one point per brick. The model in the bottom is divided into a series of segments, with each one having a simulation point. Illustration by author.

The parametric model is created from an initial catenary geometry developed by Dave Stasiuk and Anders Deleuran during the Utzon(x) Summer School 2014, which again is based on the integration of the physics solver Kangaroo, developed by Daniel Piker (Piker 2013). The parametric model is 'inherited' as an experimental starting point and redefined parametrically for development by the environmental simulation model and evolutionary processes.

Brickwork has been chosen as a simple geometric element, yet with a high capacity for varied formations and with thermal capacities due to material density and surface treatment. This allows the design method to be tested in a complex solution space. By doing so, a designer can observe the variations of each iteration proposed by the evolutionary design method. In parallel to the architectural model is a set of visual graphs plotting the thermal behaviour of each iteration and how close a 'fit' the evolutionary process is to a desired solution. By having this double visual feedback, architectural digital models and graphs, the designer is able to explore both architectural visual expression and environmental thermal sensations of the architecture simultaneously. This is intended to increase the observation of discernible steps and potentially unknown phenomena, and to advance the basis for formulation of the variables that make the design space and the formulation of the fitness function that allows the evolutionary simulation to progress.

An elementary model is created to test the combined models' ability to develop a modified half-overlay brick bond. Two types of bricks are used, a near black and a bright yellow. The geometry of the bricks is the same, so that both 'lying' and 'standing' bricks can be used in the organisation of the assembly. The change of colour effectively changes the physical absorption properties, as the dark brick has a high thermal emissivity and absorption factor, while the yellow has a low thermal absorption and emissivity factor, that is, the ability of the material to absorb energy and release it again. The configuration of 'lying' and 'standing' bricks modifies the thermal mass depth and therefore also modifies the thermal storage and its temperature decrement time. The parametric model then searches for an increase in the operative temperature perceived one meter 'behind' the surface.

Following the initial application of a simple assembly of bricks on a planar surface, the larger and more complex geometry of the Utzon(x) Pavilion is used as a basis for further study. With the multiple thermal parameter output provided from the thermal environmental simulation, it is possible to formulate both single- and multi-objective search processes. Varying the curvature of the vault surface, the orientation of the overall pavilion form, the colouration and the displacement of the bricks within the brickwork bond create the variables that can be modified during a search process. Intuitively, the surface curvature and orientation of the geometry affect the ability of the architecture to receive solar energy at different surfaces at different times of the day and year, while the change of colour changes the absorption/emissivity properties. Theoretically, the latter has a profound effect on the change of surface temperature on the externally solar energy-exposed surface and a profound effect on the ability to transfer solar energy to an internal surface from which heat is radiated into an internal space.

The resolution of the simulation points within the model can be adjusted by assessing every brick in the assembly to a resolution of one evaluation point per square meter. Furthermore, groups of simulation points can be selected to create a simulation

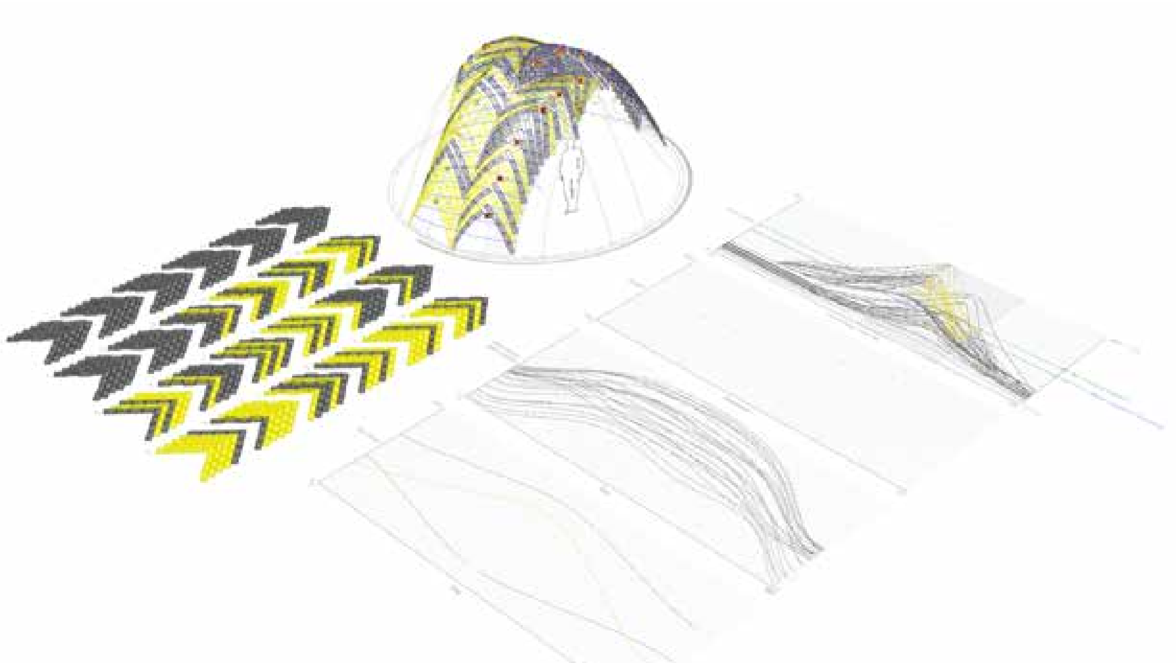

Figure 5:
Perspective view of design interface and development of pavilion in relation to orientation, vault curvature, brick-bound displacement and brick colouration. Illustration by the author.

of a selected area. The study uses the reduced simulation resolution, applicable to the specific study of early design phase explorations. This decreases computational costs and allows the designer to observe a set of desired graphs in order to better understand and develop a design search procedure. Simulation data is plotted for each simulation point for every 15 minutes across the day and year and organised into data structures that allow the designer to select specific aspects, such as envelope external temperatures in specific time periods. This in turn enables the formulation of a fitness function that is directly related to specific thermal conditions within the model. To extend the instrumentality and readability of the progressive search process, each simulated segment of the pavilion geometry is represented by a masonry bond, illustrating the brick displacement and colouration of the, in this study, herring bone bonding pattern. A designer is then able to observe and explore a design process on different design scales, overall geometry, and material assembly and physical characteristics represented in the graphs simultaneously.

Results

With the intention to study the organisation of matter across a larger enclosing surface, through evolutionary processes, a specific design method, including a new thermal environmental solver, has been presented. This model has then served as the experimental basis for developing an environmental tectonic probe for further examination.

Specifically, the study finds that:

The presented design method and model are able to articulate thermal environmental aspects at both global (formation) and local (element) scales of complex architectural structures by progressive, discernible steps. Through the integration of visual and thermal aspects, an articulation of temporal atmospheric phenomena has been illustrated, moving towards an increase in the perception of both built and natural environments. This leads to an increase in environmental sensory perception resulting in an increase of aesthetic articulation (Heschong 1979) and the production of beauty, according to Böhme (Böhme 2010; Böhme 2005).

The integration of visual geometric and graph feedback to the designer enhances the reading of the form and material development and the ability to reformulate the variables for new search processes.

This effectively supports the design relationship between the human making agent, the evolutionary process as a design agent and the environment as a design agent. The aforementioned iterative procedure of sketching-analysis-synthesis is then to be understood as a collaborative process between the above agents, rather than an iteration loop by a ‘single’ designer.

Conclusion

The application of different thermal matter elements organised through brickwork by a change of colour appears to have profound impact on both tactile (thermal) and visually based sensations. When observing the data graph output representing the computed temperatures, a significant change in the external temperature can be observed, while only a small effect is registered in the perceived operative temperature one meter inside the pavilion envelope. This condition is arguably based on the high ventilation rate in the open structure. This leads to the discussion of whether open architectures always increase the sensing of the environment. In this case, the porosity decreases the thermal

Figure 6:
Rendering of pavillon assembly with outer layer of vaults in dark brick and inner vault layer and arches in light brick.

radiant and the convective impact on the sensing human.

The thermal lag, due to the materialisation and relation to the climatic context, alters the causal effect and thus the conditions for the search criteria logic. With the thermal effect perceived in different tempi, search processes must include information on temporal environmental and occupancy conditions. The cause and perceived effect relationship is displaced in time. The study integrates such dynamics, but without the integration of occupancy patterns, as these dynamics cannot be correlated within the presented search process.

The study applies many operational design variables. These variables expand the search space and enable a potentially high differentiation of elements across the envelope formation. However, while the experiment's applied search processes were creating a diverse colouration across the envelope, it was decided that the physical full-scale probe is to maximise the thermal absorption on the external side of the envelope and minimise the use of dark bricks due to practical aspects of the limited amount of dark bricks. These fabrication constraints informed the model of aspects other than the sole thermal aspects presented at the beginning of the study as the main driver of the design search. This effectively introduced a 'cost' function, which, it can be argued, bears more resemblance to building conditions in practice.

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Design of Structural Skins

Daniel Bosia

Structural efficiency is not an option these days. With the urgent need to reduce the waste of energy and natural resources, structures should make efficient use of materials to reduce the embodied energy within our built environment. This embodied energy is a function of not only the amount of materials used but also the number of components that require design, fabrication, transportation, assembly on site and maintenance. It seems that in contemporary high-tech buildings, while the volume of materials used may have been reduced compared with traditional masonry structures, their complexity has increased exponentially. Now every component of a building has a specific function, and the coordination of all these components has become extremely complex. Today's buildings consist of different distinct parts, a primary structural frame and a secondary and a tertiary structure to support the facade. This facade in itself is composed of different layers – the waterproof layer, the thermal insulation and the solar shading or rain screen as the minimum components.

The cost of structures has also become a critical parameter behind the viability of a scheme. At the turn of the century, in certain parts of the world, some investors were prepared to spend considerable amounts of money simply to create an "iconic" image. Today, even the most ambitious have refrained from the wilfulness of the previous decade. Since the financial crash of 2009, clients have requested that designs be more lean, efficient and economical. Not only is it now harder to finance projects, but an image of extravagance is no longer perceived as desirable, even with large corporations that can afford such expensive projects. Cost is a direct function of size and the volume of materials used, but more than ever, it is proportional to the time required to construct a building. The longer a building takes to be completed, the more time is required to

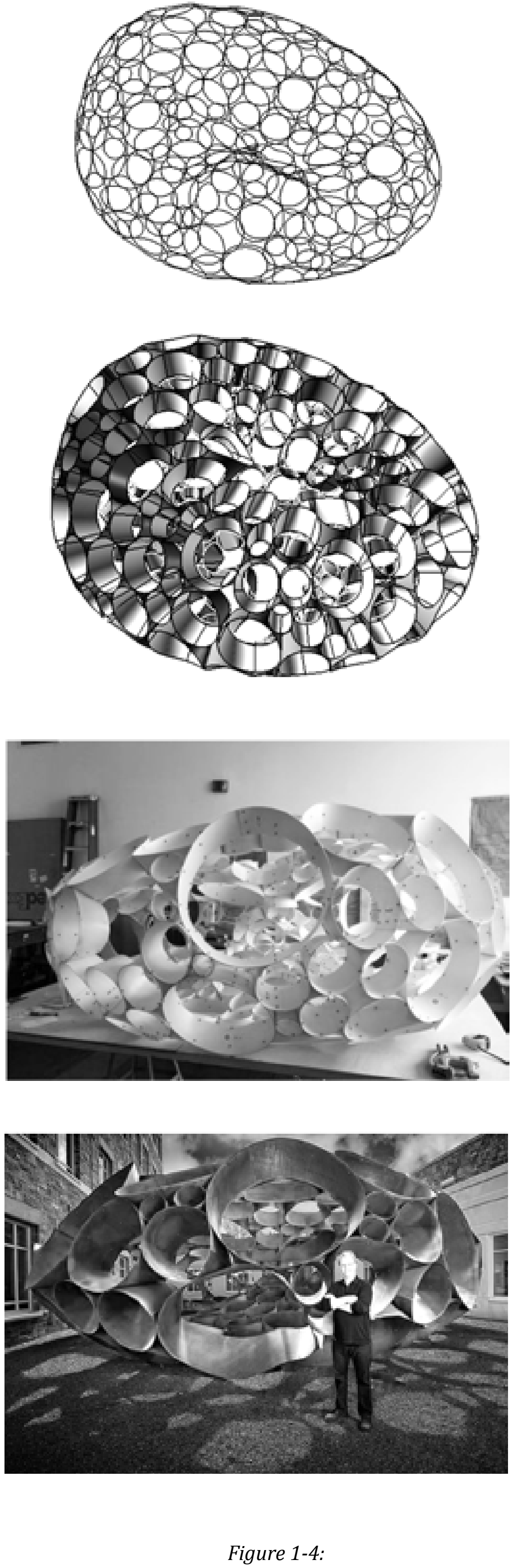


Figure 1-4:
1) Circle packing using dynamic relaxation, form-finding algorithm, 2) Conical packing formed by radial extrusion of circle packing, 3) Model of conical packing, 4) Finished installation in weathering steel, Hamilton, USA

manage its construction and the later the building can begin to produce revenue as an asset. In complex high-tech structures, coordination among the different trades on site has become one of the more expensive and risky aspects of a project.

Thus, is it possible to simplify buildings and while optimising them to reduce the amount of materials used, also decrease the number of different parts they require in order to minimise the energy and resources invested in their realisation and coordination? Could these parts perform multiple functions, as they did in traditional masonry structures, where structure also involved environmental enclosure and climatic control? Could we imagine that the "skin" of a building could be structural and continuous, realised from a single integrated layer that would perform multiple functions? It would certainly be simpler to build as it would not require the coordination of multiple components. It would also likely need less maintenance since its structural monolithic nature would make it robust and durable.

Integration

The integration of multiple functions within a single skin is one way of creating more efficient structures as a single element of a building that can perform multiple functions simultaneously. A continuous integrated skin is more complex to design than a series of separate components, each designed to carry out a specific function. The level of integration would need to be much higher since the skin would have to perform multiple functions at the same time. A continuous structure is also more complex to design because the behaviour of one part affects the whole, and it cannot be discretised and analysed in separate parts. The design and optimisation of a structural skin requires a multi-parametric design, with often conflicting parameters. As a single optimal solution does not exist, non-linear sensitivity analyses would allow the understanding of how one parameter would affect the others and would enable designers to weigh these in order to produce an optimal outcome.

Continuity

Continuity allows the properties of an element in a building to span across its entirety without interruptions, avoiding weak points at the joints between components. Structurally, continuity is a more efficient way of mobilising a structure through its global behaviour, rather than through those of its individual parts. For example, a continuous beam is more efficient than a simply supported beam. From both strength and deflection perspectives, continuous structures are more efficient and can therefore be made lighter and thinner. Several techniques exist to optimise the form of continuous structures, such as tensile membranes and shells. Digital methods of form finding have only been developed over the past 30 years. Previously, architects and engineers used physical prototypes, such as the well-known models of hanging chains that Gaudí used for the design of the Sagrada Familia. Dynamic relaxation techniques are now widely used and integrated within parametric modelling and digital design tools.

Slenderness

As structures evolve from discrete to continuous, becoming more slender due to their continuous form-found shape, and the materials available to architects and engineers possess increasingly greater strengths, their governing design parameters also change. Limiting deflections within acceptable ranges becomes more problematic than avoiding the failure of the structure. In these instances, form becomes important to provide stiffness without increasing the amount of materials used. Curving, folding, pleating and layering are techniques used in structural skins to increase stiffness without increasing

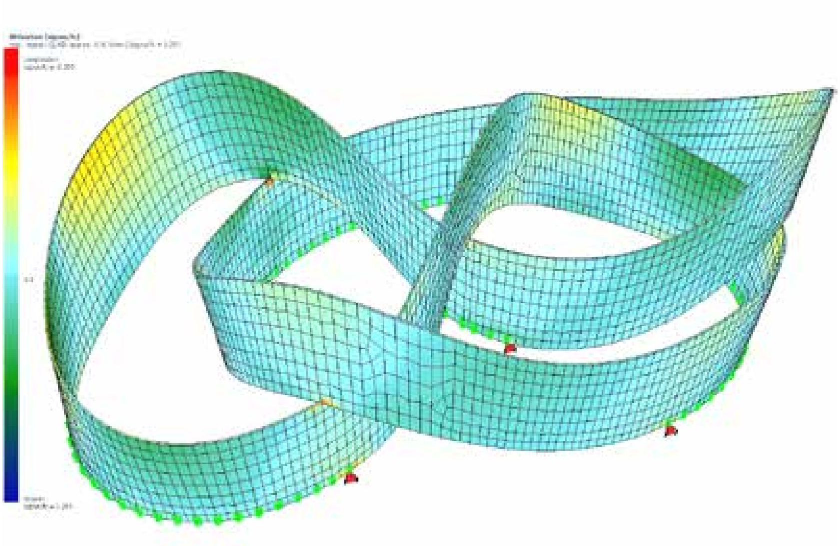


Figure 5-6:
5) Computational Dynamic Relaxation, 6) Finished installation at the Architectural Foundation, London

mass. Slenderness can also give rise to non-linear buckling effects. Again, these can be resolved by introducing ribbing and pleating of the skin. Some examples are discussed in this chapter, where a thin sheet of timber ply or steel plate is formed into curved surfaces or layered into a rigid stress skin or monocoque construction to achieve the necessary stiffness.

Dynamics

Slender skin structures are also more prone to the vibration induced by natural or artificial phenomena than strength-driven frame structures. In these structures, vibration is caused by the resonance around their natural frequency when an external periodic action is applied to them, such as wind or pedestrian footfall. The lighter and more slender a structure, the more it is usually prone to vibration. Assessing a structure's dynamic behaviour is more complex than calculating its static behaviour. Usually, a dynamic response is a non-linear behaviour; it varies in time and requires time-history analyses rather than linear static ones. It requires a detailed understanding of the material properties of the structure because mass, stiffness and viscosity directly affect its dynamic behaviour, and global strength and stability do not just involve a simple equilibrium of static forces.

New opportunities

Continuity, slenderness and its associated non-linear effects of instability and dynamic response are much more complex to simulate and understand than linear effects. These require non-linear and heavy time-history analyses.

In the past, the design of complex, continuous masonry structures was based on experience and knowledge passed from one generation to the next, an empirical art refined over centuries. Today we can predict the behaviour of continuous complex structures through digital simulations. It is now possible to create large and precise models. This has been enabled by the development of computers, whose power over the past 50 years has steadily and exponentially grown and whose cost has exponentially dropped, allowing the analysis of complex continuous, slender structures to become accessible to everyone. A finite element analysis with millions of degrees of freedom can now be solved in seconds. In the past, engineers were forced to simplify structures into basic planar and linear diagrams in order to analyse and design them by hand calculations.

Computer software has also undergone significant transformations over the past 15 years. Interoperable parametric tools now allow us to perform complex analyses in real time and inform the design of structures in a much more efficient way. The speed of analysis has allowed design engineers to use digital tools interactively by combining analogue and digital processes, analytical and synthetic ones, in much more agile forms. In other words, analytical data is fed back to the designers at a pace that allows them to make creative and intuitive yet informed design decisions. In such an interaction, the human mind and its creativity are enhanced by the analytical power of the machine. Multi-parametric sensitivity analyses are carried out, allowing designers to gain a true sense of how a structure performs, not just a final snapshot. We can pull and stretch structures to destruction almost like physical models because these digital models are capable of replicating the physical properties of the structures that we are designing.

In the following examples, structural skins are used for projects ranging from small installations to larger buildings to demonstrate their efficiency as lightweight, multi-performative building enclosures.

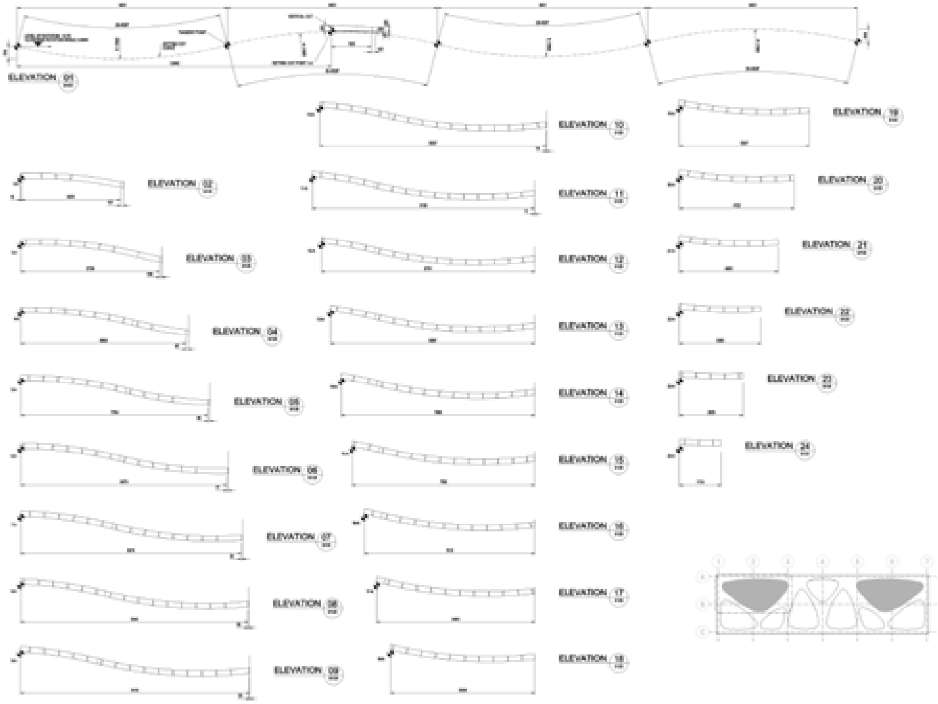


Figure 7-8:
7) BMW Pavilion, London 2012 Olympic Park – Digital fabrication drawings 8) Finished Pavillon.

Odin (Figure 1-4) is an installation designed by DeWitt Godfrey with AKT II. It consists of a series of 10-gauge conical surfaces, ranging from 300 mm to 2 m in diameter and 300 mm in depth, packed to form a flexible sponge-like structure. The curvature of the form gives the structure its stiffness. The form-finding geometry of the conical surface used a dynamic relaxation algorithm, designed to distribute the cones along the surface of the object. This algorithm ensured tangency between the cones and thus structural continuity. This simple installation demonstrates how a skin structure can be formed by discrete elements, while behaving as a continuous structural system. The slenderness of the steel plates that were rolled into cones and then bolted to one another at the points of tangency required a detailed buckling analysis to determine the non-linear behaviour of the structure as a whole.

Odin, Hamilton, USA

Designed for the Architectural Foundation in London, Tangling (Figure 5-6) is a project by Akihisa Hirata with AKT II. It consists of a timber stress skin in the form of a three-dimensional ribbon in space. Composed of two sets of cross-laminated ply sheets spaced out by a series of internal joists, the piece was built by local carpenters. It was pegged out in plan and then skinned with the ply sheets. Next, it was segmented into transportable pieces and bolted together on site through a series of bolt holes in the inner sheets of ply. The outside sheets of ply were applied on site to create a continuous smooth surface, which was rendered in white. The form-finding shape of the three-dimensional ribbon used dynamic relaxation to derive its most “natural” geometry. This prototype project demonstrates that the form finding of a structure and its digital fabrication can allow the use of relatively simple and sustainable materials and construction technologies.

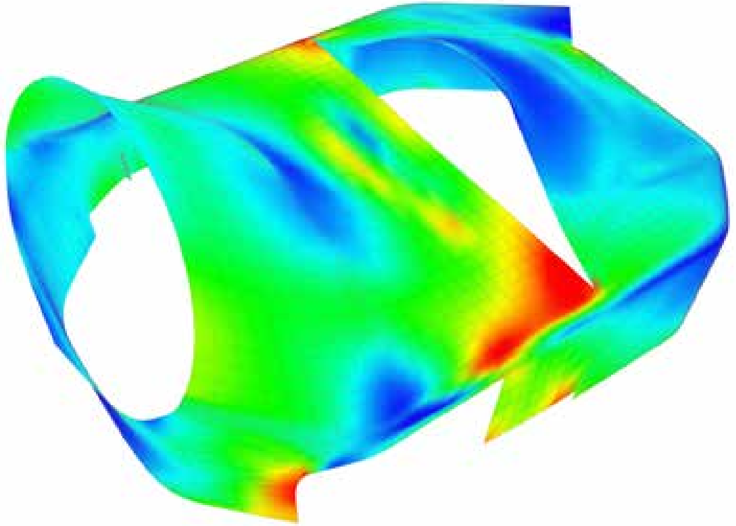
Tanling installation, London

Located in the London 2012 Olympic Park, the BMW Pavilion (Figure 7-8) comprised a series of timber stress skin roof structures spanning up to 18 m and with a depth of only 300 mm. Similar to Tangling, the BMW Pavilion stress skin shells consisted of two cross-laminated layers of ply (each 9 x 9 mm thick), separated by timber joists. These created a very efficient lightweight construction, built by local carpenters (not specialist fabricators) from detailed cutting patterns, which were produced digitally from a parametric model. The structural shells were coated with a waterproof epoxy resin and painted to provide a rain cover and a finished architectural surface. Stress skin construction is common in boat building and had been used in early aircraft, where achieving a stiff lightweight structure is key. Until recently, the building industry had not been under such pressure to reduce the weight or the use of materials, but with the current need for a higher level of efficiency, stress skin construction may become increasingly widespread.

BMW Pavilion, Olympics, London

Designed by CRAB Studio with AKT II, the Drawing Studio for Arts University Bournemouth (Figure 9-11) consists of a single steel monocoque structural skin perforated by five openings, creating five different light conditions for the artists inside. Shaped by the sun’s path, these openings are designed to receive indirect northern sky light and diffuse it on the white interior surface of the Drawing Studio in different ways. The structure consists of an 8-mm outer structural doubly curved plate, stiffened by internal 6-mm ribs at 1.5-m centres with an 8-mm internal flange to which the internal cladding is connected. The monocoque structure was prefabricated in 3 m x 15 m doubly curved panels. These were transported to the site, bolted and welded to

Drawing Studio, Bournemouth



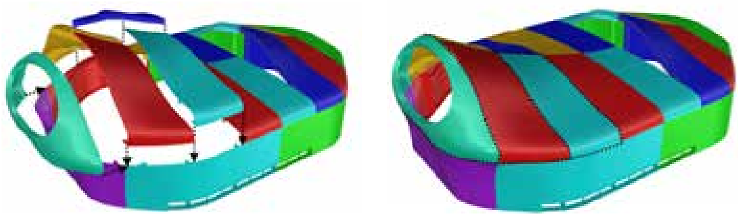


Figure 9-11:
9) Analysis by AKT II, 10) Fabrication model by CIG, 11) Finished Studio

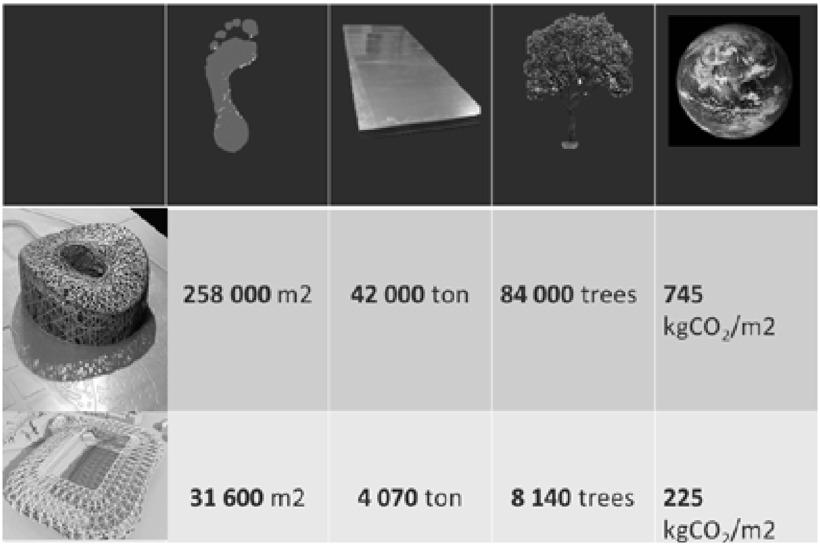
create a seamless, continuous structural skin. Painted blue on the outside, the steel monocoque forms the waterproof enclosure and is internally insulated to provide the thermal enclosure to the building. Its internal surface consists of a doubly curved plaster surface, which forms the internal acoustic and finished architectural layer of this integrated multi-performative skin.

While some of these projects are prototypical in scale and encompass a limited range of structures, from art installations to roof structures, they exemplify a design that integrates multiple functions within a single structural skin and could be extended to other, more widespread applications in the built environment. The opportunities offered by a more integrated, interdisciplinary approach to the design of buildings could lead to considerable efficiencies in the use of materials and other resources, also reducing cost and accelerating construction time. The design of structural skins will continue challenging designers to develop tools capable of analysing and solving problems from a deep understanding of their physical behaviour, as well as through closer coordination regarding their fabrication, construction and future reuse or decommissioning.

Dialectic Form

Sigrid Adriaenssens

Contemporary designers of curved structures seem to be guided by only one of the following design drivers: (i) analytical geometry, (ii) sculptural aesthetics, or (iii) structural efficiency. The behaviour of shape-resistant structures depends mostly on their global spatial configuration (e.g. shells) and less on the properties of their individual components (as in the case of frames). Analytical geometry has been used as a tool since antiquity for the generation of architectural shapes. These forms, found in the Pantheon's spherical dome (Rome, 126 AD) or Felix Candela's hyperbolic paraboloid shells (Mexico, 1950–1997), are limited by the rules imposed by analytical geometry and the designer's imagination. Recent geometrical modelling tools such as Rhino and CATIA allow more designers to base their free-form ideas on aesthetic considerations to achieve dramatic results. This design approach expresses sculptural intentions, as experienced in Gehry's Bilbao Guggenheim Museum (Bilbao, 1997), but it is disconnected from any intent aimed at structural efficiency. This design methodology needs a good team of engineers and contractors to make the sculptural form stand up, supported on an add-on uneconomic structure. The complex curved surface design challenge lies in determining the 'right' structural shape that will resist loads within its surface without the need for extra structural systems. Our research entertains a dialogue between structural curved form and other non-structural design drivers, an approach we refer to as 'dialectic' form-finding. The word 'dialectic' stems from ancient Greek and refers to a method of argument for resolving disagreement. In the context of our research, it stands for the resolution of competing (and sometimes conflicting) design drivers through a rational engineering approach. Typical design drivers for urban infrastructure are cost, technical quality (structural, environmental and construction



	258 000 m2	**42 000** ton	**84 000** trees	**745** $kgCO_2/m2$
	31 600 m2	**4 070** ton	**8 140** trees	**225** $kgCO_2/m2$

Figure 1:

Table showing quantities of footprint (first column), tonnage steel (second column), number of trees to be planted to offset steel manufacturing CO2 emissions (third column), mass CO2 emissions/ m2 (forth column) for the Beijng National Stadium (first row) and the Royal Sporting Club Anderlecht Stadium (second row).

efficiency), urban planning (context sensitivity) and architectural design.

The projects presented in this chapter focus on dialectic forms driven by structure, construction, exotic material and environment.

The first project focusses on dialectic form driven by structure and construction. The construction industry is one of the most resource intensive of all business sectors. In recent years, research in the field of sustainable structure design has mainly focused on quantifying the environmental impact and lifecycle cost of existing structures. The lifecycle assessment approach quantifies the environmental effect of a design once the design is completed. Unfortunately, little attention has been paid to developing structural design methodologies and tools that advocate sustainable design through minimal use of materials. Traditional structural design is aimed at well-defined codes that guarantee structural strength and serviceability. These codes, however, set no specific requirements regarding the structure's environmental impact. Due to the challenges of building more economically and sustainably, structures should be conceptualized with material and current available fabrication techniques in mind. The advent of digital modelling, optimization, form-finding and manufacturing technologies has given designers new tools for their toolbox. Form-finding is the process of generating shapes that are in static equilibrium for a pre-defined set of boundary conditions, including internal and external loading, support conditions and element and material properties. A comparison of two similar-looking lattice roofs, the Beijing National Stadium (Bird's Nest, Herzog and de Meuron, 2008) and the Royal Soccer Club Anderlecht roof (for Ney and Partners, 2008) — a structure for which we performed the form-finding — reveals steel quantities and associated CO2 emissions of 430 kg/m2 versus 130 kg/m2 and 745 kgCO2/m2 versus 225 kgCO2/m2, respectively (shown in Figure 1). This comparison clearly shows that form-finding techniques have the potential to generate structurally stable shapes that are financially and environmentally sound.

The development of our numerical form-finding algorithms and tools builds on research that derived beam algorithms for a form-finding technique based on dynamic relaxation. These beam and other newly developed co-planar algorithms made the design and construction of the steel and glass grid shell over the Dutch Maritime Museum possible (Ney and Partners, Amsterdam, 2011) (Adriaenssens et al., 2012).

In the late 17 century, the historic stone building that now houses the Dutch Maritime Museum was an instrument and symbol of Dutch maritime power (see Figure 2). The development of the Dutch seafaring nation was closely linked to the production of sea charts and the associated sciences (particularly geometry, topography and astronomy). This building, a former warehouse, used geometry as a basis for its design and in 1970 seemed particularly suitable for a museum. At the beginning of the twenty-first century, the building no longer met the museum's needs. As a result, a design competition was held to cover the courtyard, as a reception area, with a translucent roof. The design brief stipulated that the new design should not damage the historic building and that any addition or change to the building's heritage should be reversible. Laurent Ney chose the initial two-dimensional geometry for the steel and glass roof in order to tell the visitor a story about the building's history and its close relationship to the history of the sea. At the origin of this 2D geometry lies a loxidrome map with 16 wind roses, a figure used to mark out the course for ships (see Figure 3). This geometric pattern is found on every sea chart of the seventeenth century, the time period during which

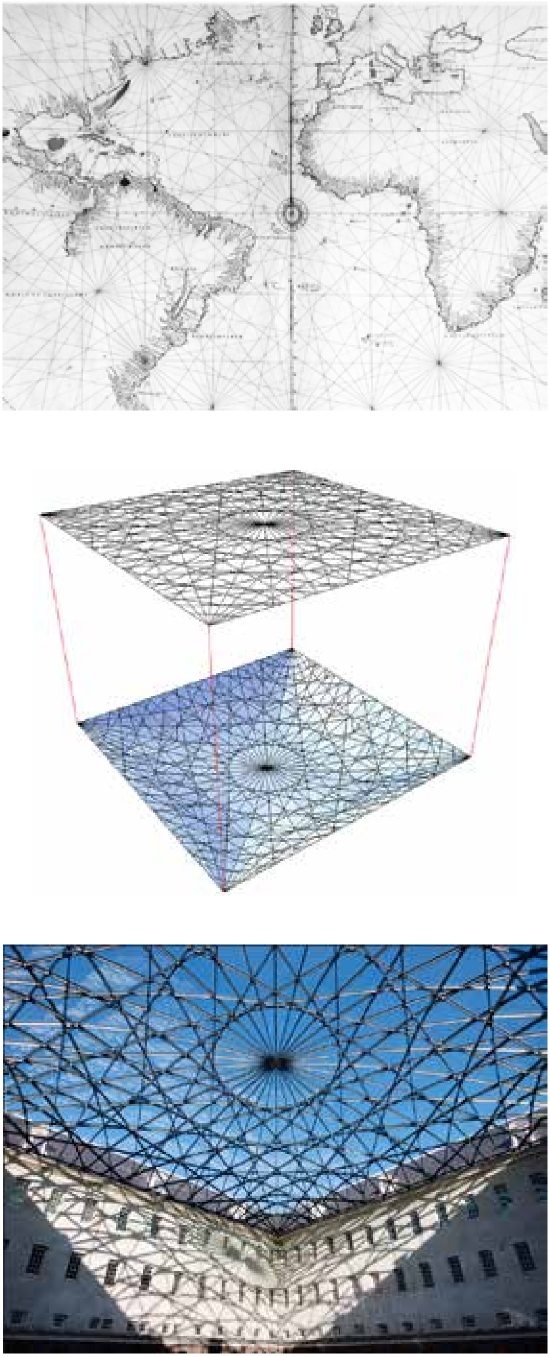


Figure 2-4:
Original loxidrome map, visualisation digital hanging chain model, interior view courtyard
Photo credit (Ney and Partners sa, 2006)

the museum was built. This pattern forms the basis for the structural mesh of the proposed steel grid shell (see Figure 4). This mesh references the power of the Dutch fleet and reinstates this former admiral building as a symbolic centre of the Dutch mastery of the seas. The multi-axisymmetric mesh also reinforces the monumental architecture of the seventeenth century building. Based on this strong contextual mesh, we developed form-finding techniques and facet planarity algorithms to stir the form of the steel/glass grid shell shown. The issue of facet planarity required for use of glass panes imposes a slight modification of the form-found geometry of the shell. For this project, a specific method based on origami folding was derived. Sometimes, planarity of mesh might not be desired (e.g. Foster and Partners' design for the Smithsonian Institute). Because of steel digital fabrication techniques pioneered in the design of the roof over the great courtyard of the British Museum, standardization of meshes and, thus, elements and nodes, is no longer considered crucial, but mesh planarity of non-triangular meshes is still a vital issue. This realized structure has been well received and appreciated by its local community, its users and peer professionals, and it won the 2012 Amsterdam Architectural Prize as well as the 2012 Dutch and Belgian Steel Award. De Groene Amsterdammer, the local newspaper from Amsterdam, writes about the joy of experiencing the cupola: 'Of course, we all envy the museum's night guard who gazes at the stars through the 1016 pieces of glass that make up the magnificent cupola designed by Laurent Ney. At least when the courtyard is not populated with adults and children, sitting on the floor eating their homemade sandwiches.'

The second project we discuss reflects our approach to dialectic form driven by considerations of structure and unconventional material (Jordan et al., 2015). This project was carried out in collaboration with Professor Axel Kilian (School of Architecture, Princeton University) and Mark Adriaenssens (Barry-Callebaut).

When first introduced to the idea of using chocolate as a building material, we jumped to the imagery of Charlie and the Chocolate Factory. Just as the appeal of Willy Wonka's factory lies in the technological complexity of his extraordinary uses of chocolate, the challenge of this project was to utilize novel design practices to create a structural system that allows chocolate to be seen from a new perspective as an experimental building material. Chocolate is often used for artistic purposes, but using chocolate as a structural material and not just as a sculptural medium poses significant challenges. Since chocolate has never been analysed as a structural material, we first determined which chocolate formula best suited this purpose and what engineering properties could be expected from it. Table 1 compares the properties of the most appropriate formulation with the more common structural materials steel and concrete. The properties in the table as well as the material's high creep rate suggested the necessity of form-finding techniques to generate membrane/shell systems that would reduce the material stress and size optimization and bring the self-weight down.

Table 1 Comparison of material properties with common engineering materials.

Material	*Strength (N/mm2)*	*Density (kN/m3)*	*Young's modulus (kN/m2)*
Steel	413	76.98	199 × 106
Concrete	27	23.56	29 × 106
Chocolate	0.6	12.88	45 × 103

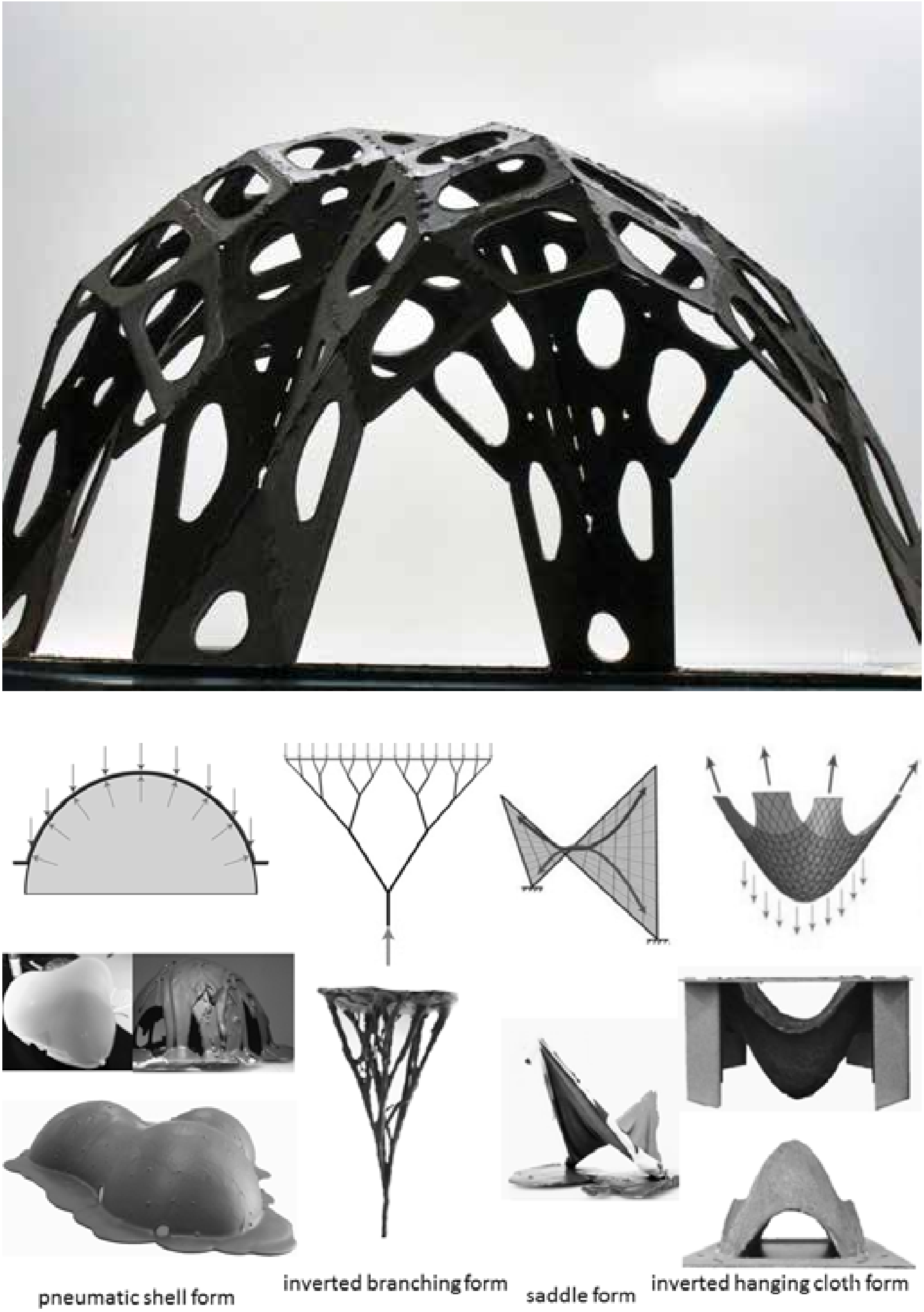


Figure 5:
Physical and numerical form finding experiments, chocolate prototype Photo credit Axel Kilian.

In order to find a suitable structural typology for chocolate, physical form-finding experiments were employed. These experiments allowed exploration of the less quantifiable properties that affected the potential designs. Experimentation based on chocolate's rheological properties, such as dependence of the viscosity on temperature, layering based on surface tension and the visual quality of the surface, changed how the material read aesthetically. Four different historic physical form-finding techniques that lent themselves to this application were used for the fabrication of small models. The techniques were pneumatic shell, inverted branching form, saddle form on flexible formwork and inverted hanging cloth form, as shown in Figure 5. These models were analysed based on structural ability, ease of construction, and aesthetic expression. With only the self-weight of the material to carry, the catenary hanging cloth form was the most structurally efficient. As long as creep and global buckling were considered in the design, it provided the system that could span the farthest using the smallest amount of material.

Based on the findings of the physical material–driven explorations in shape generation, a structural system was chosen where the form is found using the hanging membrane technique but construction is facilitated via a precast segmental approach. Because the site and boundary conditions for this project were unknown and subject to change, the ability to explore various designs quickly was desired. An integrated parametric workflow was created for form-finding, void optimization and mould layout to minimize self-weight. Pre-casting planar pieces allowed for best control of material quality but added further design constraints. The parametric programming environment used for this project was Grasshopper 3D, an extension of Rhinoceros 3D. It was chosen not only for its ease of use but also for its plug-in framework that allowed programs with varying functionalities to be combined together to create an integrated system. This integrated process enabled enhanced design exploration and reduced errors in translation of structural models to output data.

Most existing large-scale chocolate artefacts are representational sculptures, not performance-driven structures. Structurally, they rely on 'mass' rather than 'form' to carry their self-weight. With no prior published numerical, experimental or analytical results for large-scale chocolate structures, creating prototypes was essential to (i) validate the feasibility of the proposed design and construction approach and (ii) confirm that the shell does not exhibit creep-triggered buckling or other additional unpredicted structural failure mechanisms. We therefore constructed a small-scale mock-up, shown in Figure 5, that shed light on the viability of the digital workflow and the real structural performance.

By applying existing form-finding and optimization techniques within a parametric formwork tailored to meet specific site constraints, we had the freedom to explore and play with a realm of efficient and constructible forms, brought forth by the intrinsic qualities of chocolate. With the adoption of this approach, the success of the design is very much in the designer's hands — factors from the initial geometry to the various choices made during the design process affect the efficiency of the result. For example, the choice of initial mesh density means a trade-off between number of moulds and size of members. This understanding expands into the concept of discipline and play, the terminology used to describe the conflict of emphasis that distinguished early shell designers. In a sense, this system provides both — the parametric framework imposes the discipline while leaving the designer the freedom to play with form. The chocolate

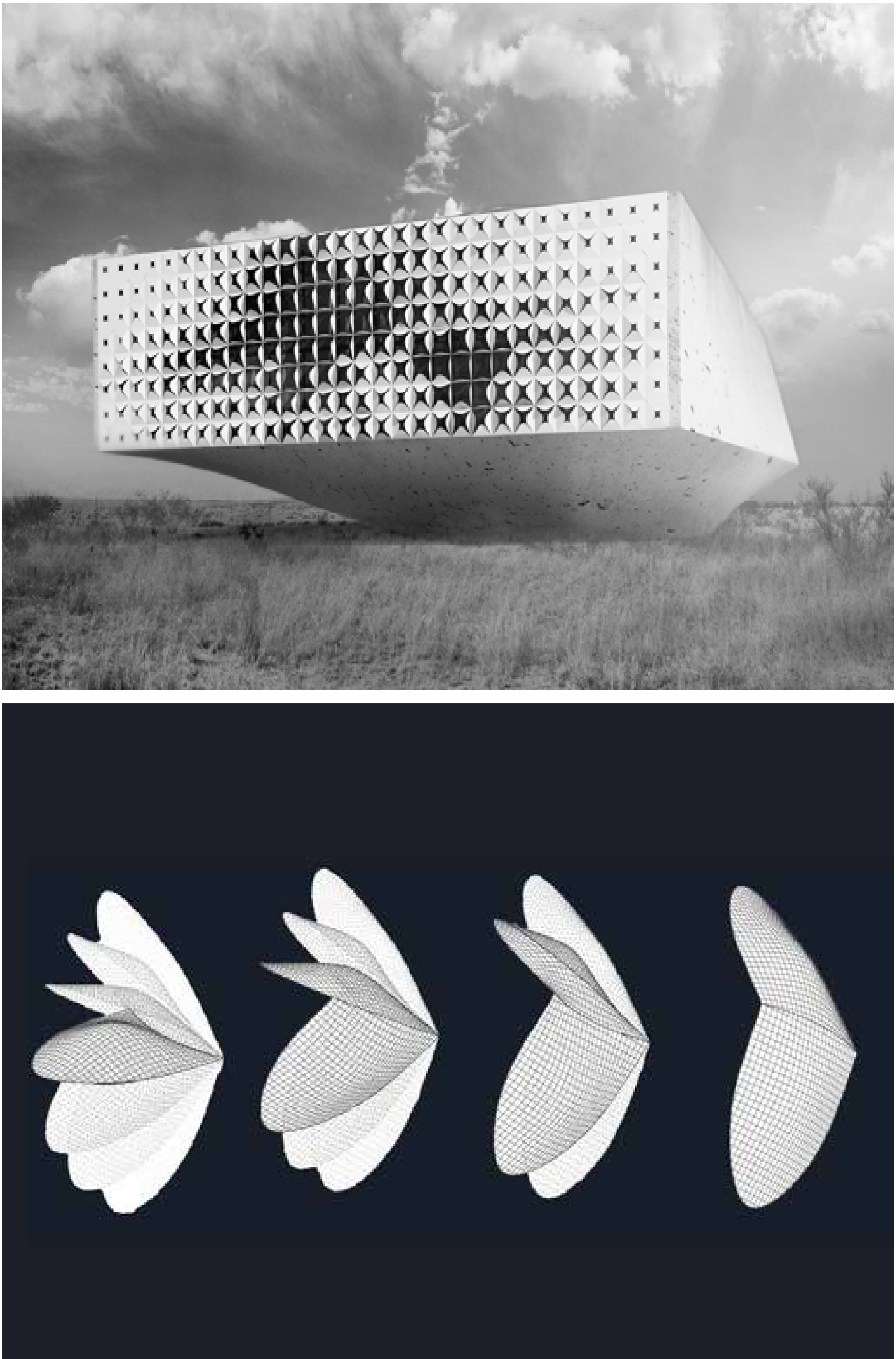


Figure 6-7:
Visualisation of adaptive façade modules, ghosted motion of shading module.
Illustrations by Sigrid Adriaenssens

material builds on this idea of play — the designer is looking for ways to express the material within the design in an experimental fashion. This exploration of material proves important to choosing forms that express structural and aesthetic values, not just for Willy Wonka but also for designers who wish to engage in material-driven design exploration.

Finally, we show how our approach to forms is driven by structure and environment. Most building enclosures in the United States are designed to shelter and protect their occupants by making the indoor environment insensitive to its exterior surroundings. Consequently, an awkward amount of mechanical and electrical systems must be installed, run and maintained to condition this environment by heating, cooling, ventilation and artificial lighting. Although this design philosophy might create a productive and pleasant space, this realization occurs at the expense of energy consumption and, hence, the use of natural resources. In contrast, ancient vernacular and bioclimatic architecture considers the outdoor environment as a design driver in the building enclosure design process. In this respect, the role of the building enclosure becomes important as it is at the interface between the indoor and outdoor environment. The design of an adaptive dynamic shading enclosure requires an approach that uses environmental performance, structure and kinetics as design drivers. Adaptive dynamic building enclosures must respond and adapt to multiple design variables such as weather, context and occupancy. The interactions among these variables are inherently dynamic, non-linear, stochastic and multi-dimensional. These features, in general, have led to the development of adaptive building skins, which have already proved significant operational energy saving potential, by as much as 51%. The logic of adaptive performance is compelling: it promotes reduced energy consumption and increased occupant comfort. Although the performance of adaptive enclosures might depend upon the occupants, its efficacy meets or exceeds that of a fixed system. However current dynamic adaptive building enclosures rely on a large series of mechanically complex hinges and costly actuation systems to adapt their shape. The shell module presented in this section (Adriaenssens, et al., 2014), challenges the promotion of such systems with kinematics based on elastic structural deformations. The proposed module shows that elastic deformation can be a successful shape-shifting strategy for lighter and mechanically less-complex dynamic adaptive façades.

Figure 6 shows renderings of the presented adaptive dynamic shell module on the exterior façade of a south-facing façade near Austin (Texas, USA, latitude: 30.21N). The opacity of the façade can be varied in response to external and internal conditions. Depending upon the architectural program behind the façade, a varying degree of opacity might be desired during different seasons and at different times of the day. To design a high-performance dynamic shading enclosure that is integrated, multifunctional and adaptive while using minimal operational energy, two concepts are important: complexity and kinetic amplification. In a complex system, a small change in one part cascades down into the other parts and gives rise to collective, emergent behaviour of the entire shading system. In particular, in the context of a dynamic adaptive shading enclosure, a single degree of freedom of motion in one component would give rise to an emergent motion of the entire shading module. To minimize operational energy, the applied actuation would also have to be small and result in a controlled shape transformation of the shading module over a wide range of opening or closing stages.

This concept is termed kinetic amplification and results in an energy-efficient kinetic system. The dynamic shell shading module controls solar radiation in an active manner: it repeatedly and reversibly shift its shape to improve the building's environmental performance. The structure and kinematics of the shading shell module are integrated in a complex system, where shape changes emerge from a multiplicity of simple interactions (i.e. the bending of the connecting beam cascades down in the amplified closing movement of the connected shells) (see Figure 7). The proposed system can maintain a high performance level through shape control when operating conditions or functional requirements (such as architectural program) change in a predictable or unpredictable way. It can thus make transitions over time, meet new objectives and cope with uncertainty by exploiting changes in its environment.

Conclusion

Under the increasing pressure of emerging megacities, climate change and fossil fuel dependency, we will have to devise strategies to provide for more people with fewer resources. As the gamut of competing and possibly conflicting design criteria for urban infrastructure expands, new approaches will be needed that resolve the dialogue between those different criteria. In this chapter we have shown, using three projects, how dialectic form-finding has great potential to tackle those challenges in one integrated system. By relying on ingenuity of form rather than (for example) mass, this approach yields innovative systems that are efficient with regard to both material and environment. This research by design suggests that there is a large unexplored design space of systems, with urban applications, waiting to be discovered.

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Fabio Gramazio and Matthias Kohler

Fabio Gramazio and Matthias Kohler are architects with multi-disciplinary interests ranging from computational design and robotic fabrication to material innovation. In 2000, they founded the award winning architecture practice Gramazio & Kohler and since 2005 they jointly run the Chair for Architecture and Digital Fabrication at ETH Zurich. Current projects include the design of the Empa NEST research platform, a future living and working laboratory for sustainable building construction. Opening the world's first architectural robotic laboratory at ETH Zurich, Gramazio & Kohler's research has been formative in the field of digital architecture, setting precedence and de facto creating a new research field merging advanced architectural design and additive fabrication processes through the customised use of industrial robots. This ranges from 1:1 prototype installations to the design of robotically fabricated high-rise buildings. The research is outlined and theoretically framed in the books Digital Materiality in Architecture (Lars Müller Publishers, 2008) The Robotic Touch: How Robots Change Architecture (Park Books, 2014) and has been presented at the Venice Architecture Biennial, the Chicago Architecture Biennial, Storefront Gallery NY, Sitterwerk St. Gallen and FRAC Centre Orléans.

Tobias Bonwetsch

Tobias Bonwetsch is managing director of ROB Technologies, a company that provides solutions that enable highly flexible robotic fabrication processes for the efficient production of building components as well as individual nonstandard parts. He studied architecture and graduated from the Technical University of Darmstadt. He completed his postgraduate studies at the ETH Zurich with a specialisation in Computer Aided Architectural Design. In 2005, Tobias Bonwetsch joined the group of Gramazio Kohler Research at the ETH Zurich. His research is concerned with integrating the logic of digital fabrication into the architectural design process, with a special focus on automated assembly processes. As a result, a robotic-based technology for the design and assembly of brick facades was developed and successfully commercialised in 2010.

Lars Juel Thiis

Lars Juel Thiis is founding partner of Cubo architects, established in Aarhus Denmark in 1992, when they won an open church competition. Since then competitions have been part of the raison d'etre of a practice mainly concerned with educational and cultural buildings. The focus of Cubo has been an insistence on the importance of site and setting thus each project is different, designed in the circumstance of time.

Thiis is an adj. professor at Aalborg University, and holds influential posts in the cultural sector. Thiis chairs the Council for Listed Buildings (Det Særlige Bygningssyn), he chairs the censorial system of the Educations of the Arts and also the advisory board for competitions in the Architectural Association.

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Sigrid Adriaenssens focuses on one of the most exciting and innovative areas of structural and architectural engineering concerns—the exploration of thin forms as possible alternatives to a world of shrinking material resources. She is an associate professor at the Department of Civil and Environmental Engineering at Princeton University where she leads the Form Finding Lab. Prior to academia, she was a project engineer at Jane Wernick Associates (London, UK) and Ney and Partners (Brussels, Belgium). Her research, design and teaching have been awarded a number of prizes including the IASS Tsuboi Award and the Alfred Rheinstein Award.

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Mette Ramsgaard Thomsen is Professor and leads the Centre for Information Technology and Architecture (CITA) in Copenhagen. Her research examines how computation is changing the material cultures of architecture. In projects such as Complex Modelling and Innochain she is exploring the infrastructures of computational modelling including open topologies and adapative parametrization. Her research is design led and explores the implications of computational design and its materialisation.

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Kjeld Ghozati

Kjeld Ghozati (1969) was born in the town of Billund in Denmark where LEGO also was founded. He is educated constructing architect from Horsens Polytechnic in 1993 and architect from The Aarhus School of Architecture in 2001. In 2003 he became partner at Exners Tegnestue in Aarhus. In 2012 the office changed its name to E+N Architecture. He has received several architectural prices for inner city projects specially for infill projects in the city of Aarhus. In 2016 he founded the configuration lab ARINSTO. The ARINSTO name is short for architects, inventors and storytellers. He has among other things invented the Flex Brick System and the architectural method ArchiShapes and is the author of the leadership book: BullseyeDNA – creative power, humility and generosity.

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Daniel Bosia

Daniel Bosia, Director at AKT and head of the P.ART team, is a Fellow of the Institution of Structural Engineers with an MSc in Structural and Bridge Engineering and a Master Degree in Architecture. He has worked at Arup for more than twelve years, collaborating with architects including Daniel Libeskind, Toyo Ito and Enric Miralles and with artists like Anish Kapoor, Antony Gormley and Matthew Ritchie. A cofounder of the Advanced Geometry Unit at Arup (AGU), Daniel has designed and delivered several complex and iconic art and building projects. Diploma Tutor at the AA and Honorary Professor at Aalborg University, he has lectured in many Universities in Europe and the US including ETH, UPenn, IIT, Yale, Columbia, Princeton.